1160 AD A132448 1549

JUNE 1983



R and D CENTER LABORATORY

TECHNICAL REPORT

NO. 12758

# DEVELOPMENT OF RECUPERATOR MANUFACTURING TECHNIQUES

Contract Nos. DAAK 30-77-C-0078 (Phase I)
DAAK 30-79-G0045 (Phase II)

by Jule A. Miller
AVCO LYCOMING DIVISION
STRATFORD, CONNECTICUT

Approved for public release, distribution unlimited.

PROJECT ENGINEER: David Pyrce
DRSTA-RCKM

U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH AND DEVELOPMENT CENTER
Warren, Michigan 48090

20020809018

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>12758 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>Development of Recuperator Manufacturing Techniques | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final Technical Report<br>20 Sep. 77 - 31 Dec. 82 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Jule A. Miller-Avco Lycoming | | 8. CONTRACT OR GRANT NUMBER(s)<br>DAAK30-77-0078<br>DAAK30-79-C0045 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Avco Lycoming Division<br>550 South Main Street<br>Stratford, CT 06497 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>US Army Tank Automotive Command<br>Metals/Welding Subfunction<br>Attn: DRSTA-RCKM Warren, MI 48090 | | 12. REPORT DATE<br>JUNE 1983 |
| | | 13. NUMBER OF PAGES<br>118 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release,
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

AGT 1500 Turbine
Exhaust Heat Recuperator
Laser Welding
Inconel 625
Computer Control

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of an automated, computer controlled, pulsed carbon dioxide laser welding facility for joining of a thin plate gas turbine engine recuperator.

Several commercial carbon dioxide laser systems were evaluated for the application, two of them extensively. A detailed analysis and comparison of these systems is given, as is an explanation of the operation of industrial $CO_2$

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE



SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. (con't.)
lasers and the problems involved in their design and application.

The computer control of laser welding systems is discussed with particular emphasis on the use of high speed moving mirror systems to deflect the laser beam around irregular shaped joints. Control was obtained at welding speeds up to 100 millimeters per second (235 inches per minute), while joining the 0.2 millimeter (0.008 inch) thick nickel based alloy (Inconel 625) used.

Two computer/moving mirror systems were evaluated and programs for each developed. One was in ESSI, a European machine tool language and the other in U.S. computer numerical control language. The program development work and the problems in integration of computer and laser systems are discussed.

Considerable work was done to develop tooling concepts for maintaining the tight contact between components required for laser welding. This work and the design of the final computer controlled work handling and holding tools are described.

A detailed cost analysis is given, comparing laser and automated resistance seam welding for this application. An appendix discussing the management of advanced manufacturing technology programs is included.

TECHNICAL REPORT NUMBER

# DEVELOPMENT OF RECUPERATOR MANUFACTURING TECHNIQUES
PHASE II
FINAL REPORT

Jule A. Miller

Department of Army Contracts
DAAK30-77-C-0078 (PHASE I)
DAAK30-79-C-0045 (PHASE II)

Prepared by
AVCO LYCOMING DIVISION
550 South Main Street
Stratford, Connecticut 06497
for
U.S. ARMY TANK AUTOMOTIVE COMMAND
WARREN, MICHIGAN

# PREFACE

This final report describes work conducted between 20 September 1977 and 31 December 1982 by Avco Lycoming Division, Stratford Connecticut, under contracts from the U.S. Army Tank-Automotive Command, Warren Michigan. It presents the results obtained in this two-phase program in the development of laser welding techniques for fabrication of recuperators for the AGT1500 engine.

Victor Strautman served as Program manager for Lycoming in Phase I. Barton Hessler filled this position in Phase II. Jule Miller, as principal engineer conducted the technical effort throughout the program.

Acknowledgement is given to Samuel Goodman, David Pyrce and Dr. James Chevalier who administered the contract and monitored progress on the program for TACOM.

Appreciation is expressed for the contributions of Gerard Bessette, Jeffrey Thyssen, Walter Dusha, Steven Klinga, George Cygan, William Wallace and Erwin Oberhauser and Jack Lee of Lycoming; Don Bowes, Peter Allan and Pat Harris of Coherent Inc., and Robert Hills and Richard Ashcroft of Control Laser (B.O.C.).

This report is submitted in compliance with the requirements of DD Form 1664.

This project was accomplished as part of the U.S. Army Manufacturing Technology Program. The prime objective of this program is to develop on a timely basis, manufacturing techniques and equipment for use in production of Army material.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

## LIST TABLES

LIST OF ILLUSTRATIONS

## 1.0. INTRODUCTION

### 1.1. Recuperator Design Assembly.

Avco Lycoming's AGT 1500 gas turbine, selected to power the U.S. Army's M1 Tank, is a recuperative engine. The recuperator is an all primary surface heat exchanger made of thin convoluted metal plates. The exhaust from the power turbine enters the center of the annular recuperator, where it diffuses and turns radially to flow between the plates of the recuperator (Figure 1). Compressor air enters the front of the recuperator through the air inlet holes, passes between the plates, and then, via the air exit holes, leaves at the front of the recuperator. It then enters the combustor section of the engine. Preheating of the compressor air by the exhaust gases significantly reduces the engine's fuel consumption.

The AGT 1500 recuperator is sized to meet the performance goals of the engine over the entire operating range. The core is 22 inches long with an inside diameter of 15 inches and an outside diameter of 27 inches (Figure 2). The plates in the core are embossed with convolutions of two different geometries which space them at 0.040 inches and provide flow passages of suitable hydraulic diameter to produce the required pressure drops and convolution stress levels. Because of the temperature and pressure levels encountered in service, the material selected for the plates is Inconel 625 (see Appendix A).

The recuperator plates are formed of 0.008 inches thick material. The plates are first assembled in pairs by welding around the air inlet and outlet holes. These two plates enclose the gas passages and have high pressure air bearing on the outside of them. Therefore, the hole welds are not highly stressed and only seal the air from the gas. Once the pairs are joined around the holes, the plates are assembled and welded around the outer and inner diameters of the annulus to make a core. This welding operation encloses the air passages and serves once again to seal the air from the gas. Recuperator fabrication is completed by assembling and welding the header, and by final pressure testing. There is a total joint length of about 10,000 feet per core of which about 6,500 feet is around the air inlet and outlet holes.

The joining of the recuperator is actually done in two separate operations with different conditions imposed by the different accessibilities of the joints. The hole joints are readily accessible by techniques which operate normal to the plate surfaces (Figure 3). The inside and outside joints, after the pairs have been joined around the holes, are not accessible to such techniques. They require a welding process which operates parallel or at acute angles to the plate surfaces (Figure 4).

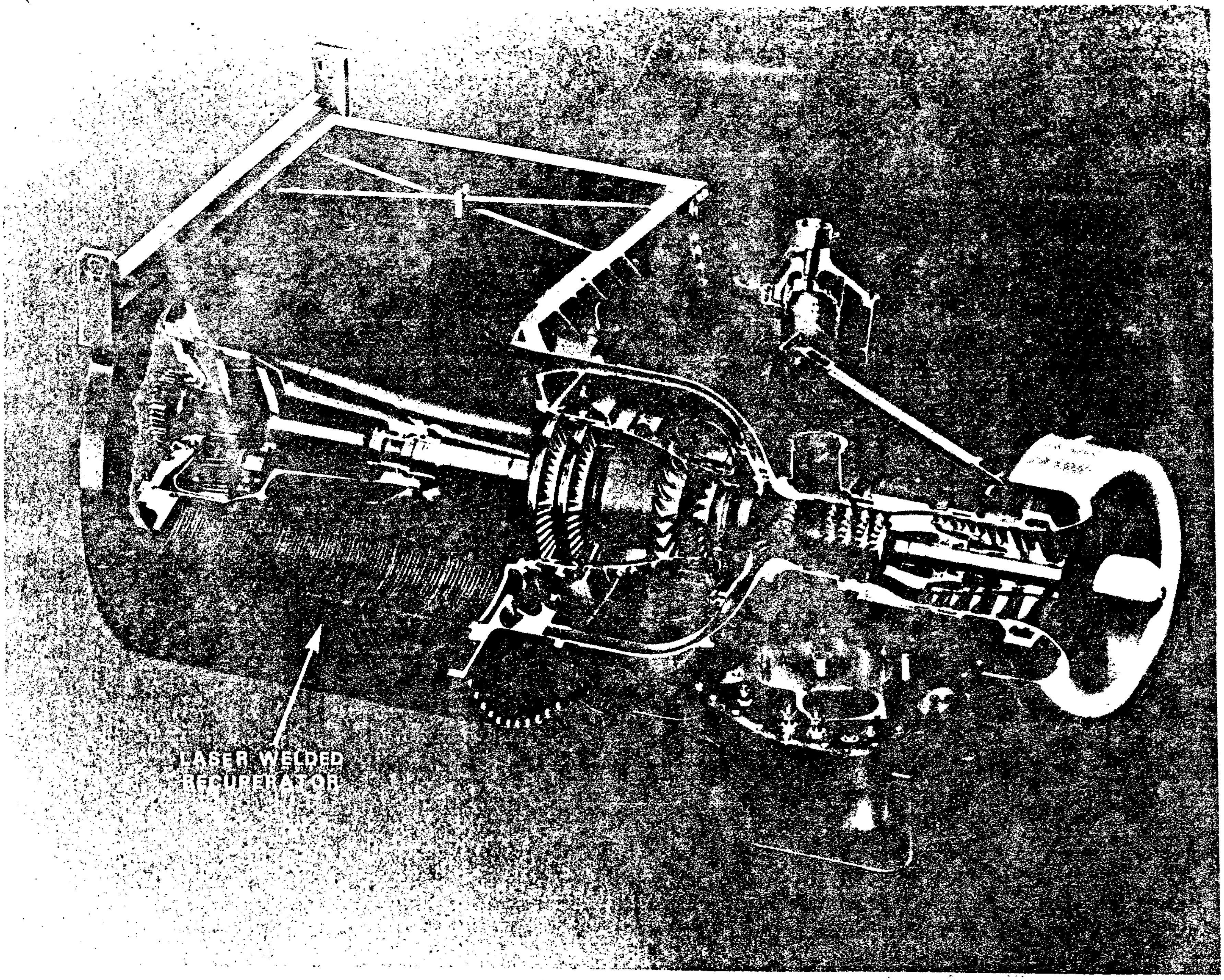



FIGURE 1. AGT1500 ENGINE

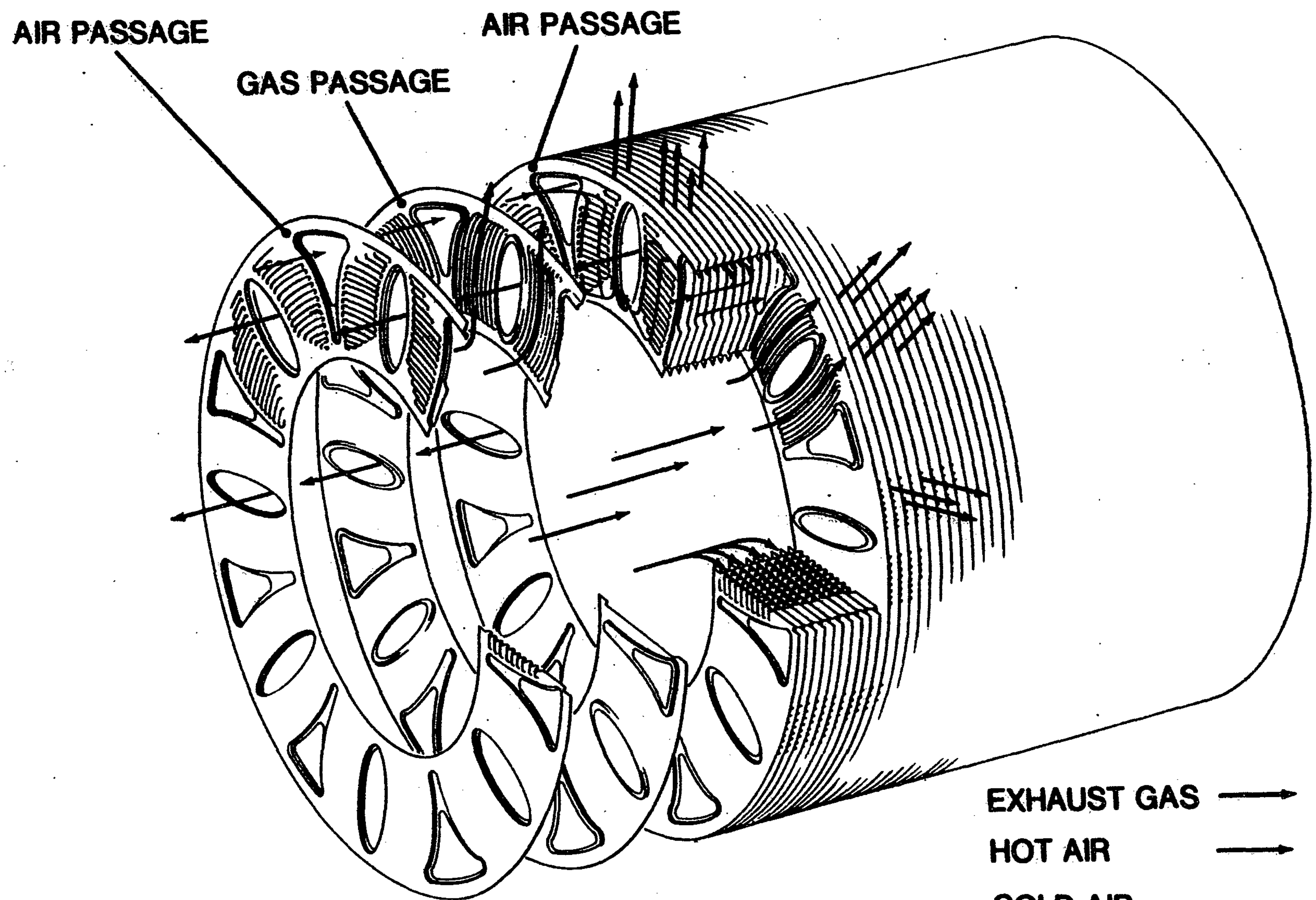
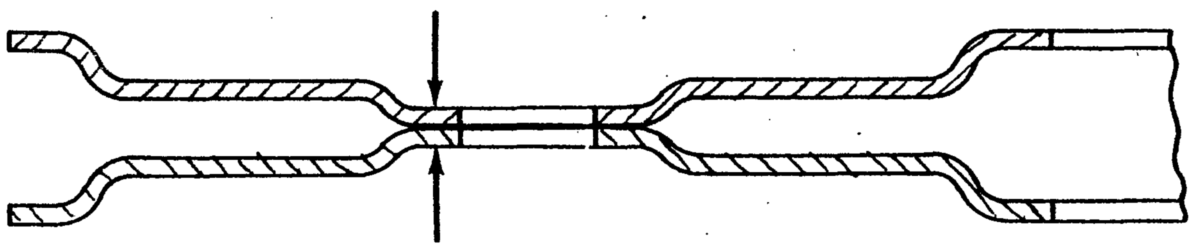



FIGURE 2. AGT1500 RECUPERATOR



BK1021

Figure 3
ACCESSIBILITY OF THE HOLE JOINTS FOR WELDING

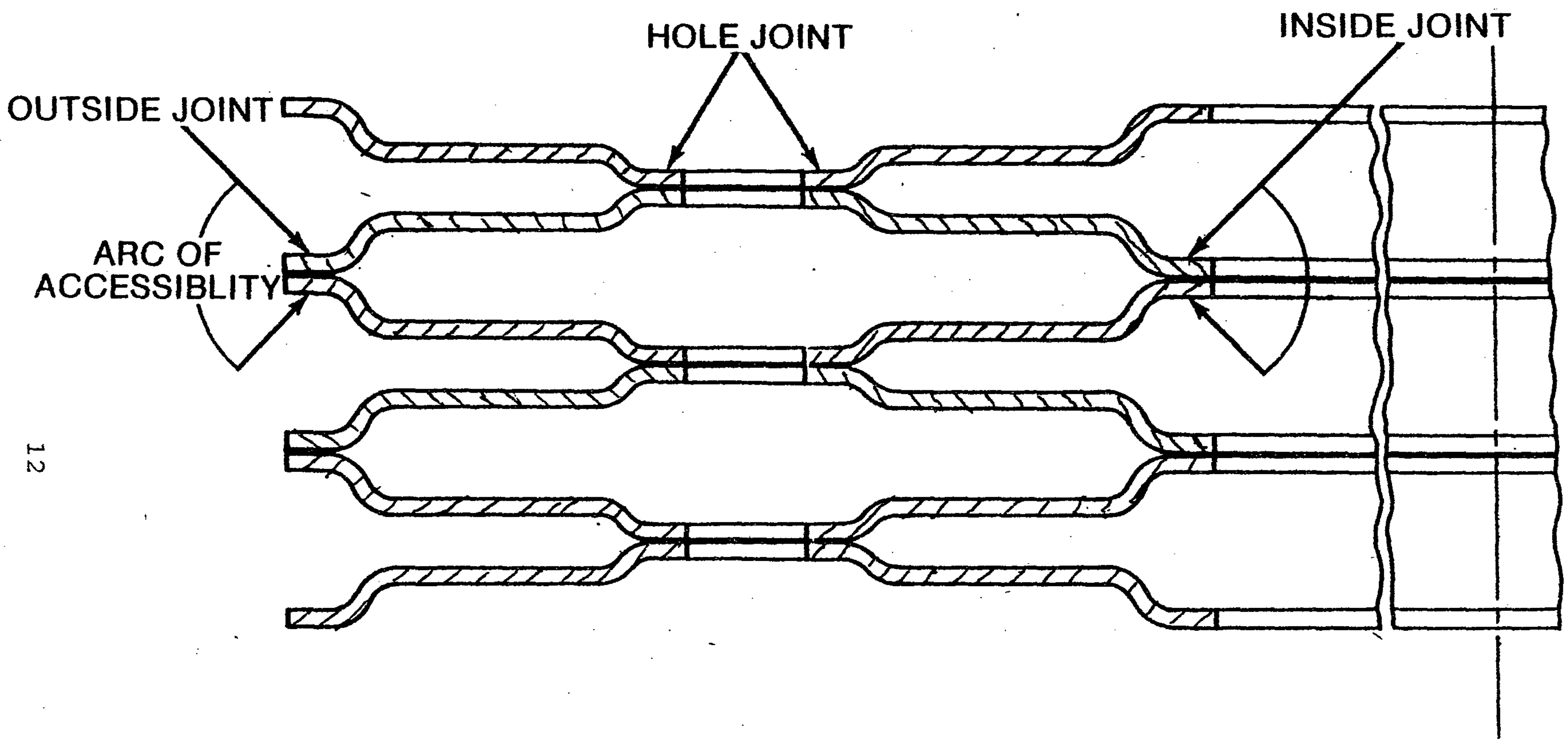



Figure 4
ACCESSIBILITY OF INNER AND OUTER JOINTS FOR WELDING

It would be theoretically possible to build a recuperator core with a welding process that operated from one side normal to the plate surface by stacking the plates one at a time and alternately welding around the holes and inside and outside joints. Laser or electron beam welding meet the requirement of welding from one side normal to the part surface, but both of these require tight metal to metal contact of the joint surfaces. The tooling required to assure this contact would make this assembly sequence impractical for a high speed automated operation. Alternately, brazing offers the important advantage of allowing all of the joints to be made simultaneously, rather than sequentially as with a welding processes. Early in the recuperator program, considerable development work was done on brazing of model parts. The extensive tack welding necessary to assure joint positioning during furnace heat up, the cost of filler metal preforms and the difficulties in reworking internal joint defects led to the elimination of brazing from consideration for this application..

Once it was decided that the best process was the two-step assembly technique of first welding the plate pairs around the air holes and then stacking them and making the inside and outside joints, welding techniques for these two different operations were evaluated.

Resistance seam welding was selected quite early in this work as the best method for joining the hole peripheries (Figure 5). Some work was done with electron beam welding for this application. But the requirement for vacuum operation complicates tooling, and increases the costs of the process. It was therefore rejected, although sound sample welds had been made. During this early development of the recuperator manufacturing process, the problems of joining the inner and outer joints were the most difficult because of the limited accessibility of the joints. Edge fusion welding of the plates by gas tungsten arc welding, and micro plasma welding were attempted and after much work, discarded. The key problem is the flimsiness of these .008 inch thick plates which causes them to move and buckle when heated. This causes the joints to separate ahead of the heat source unless rigidly held. Holding could only be accomplished by placing wire rings of the proper size between each plate pair and end loading the core to lock the joints in place. The assembly of these wires was extremely tedious and totally unsuited for a production process.Attempts at developing other tooling were unsuccessful because of the arc's inherent lack of "stiffness".

The problem of welding these joints was finally solved by the invention of an ingenious resistance seam welding device which reaches between the plates to weld them (Figure 6).

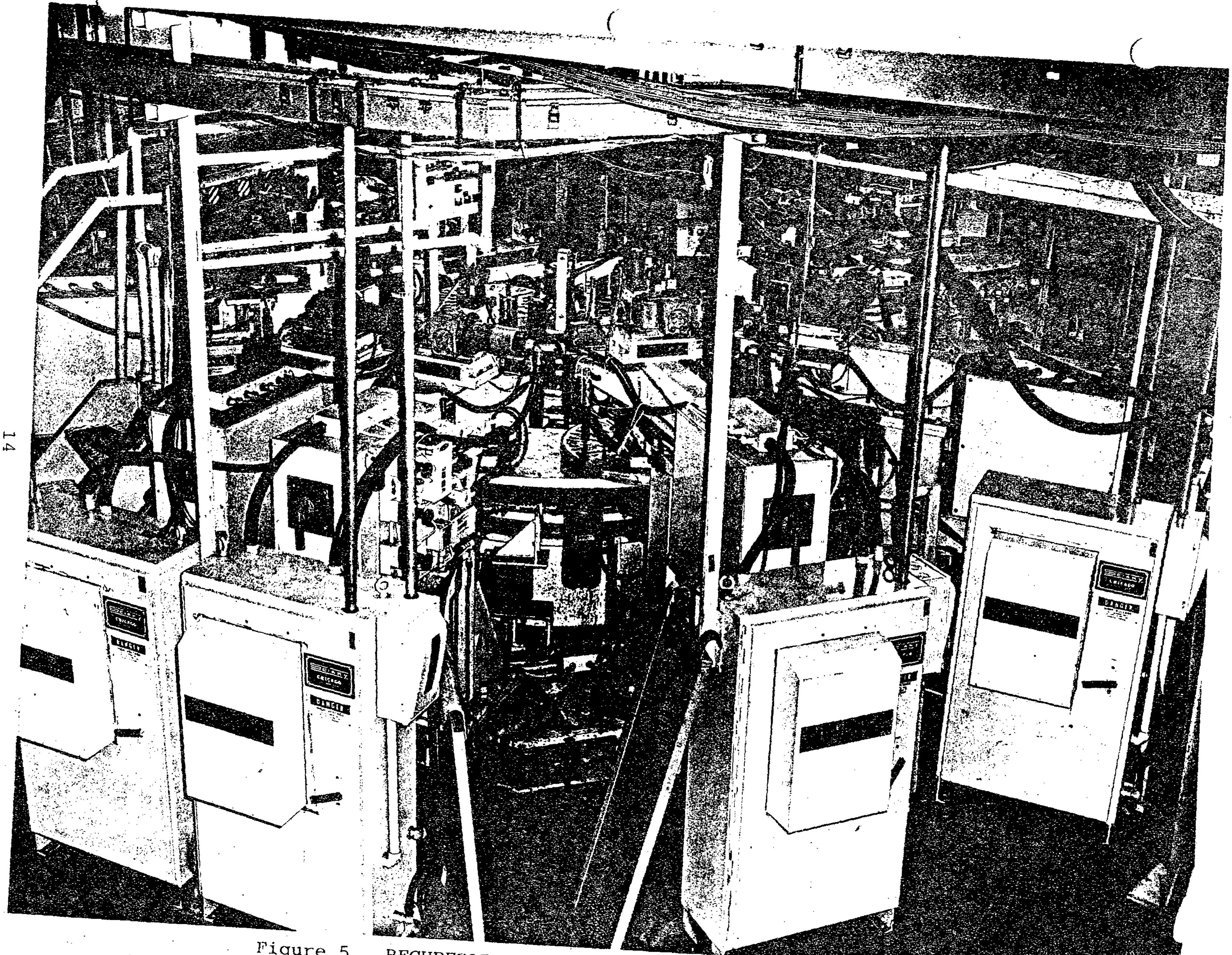


Figure 5. RECUPERATOR HOLE JOINT RESISTANCE WELDER (DIAL FEED)

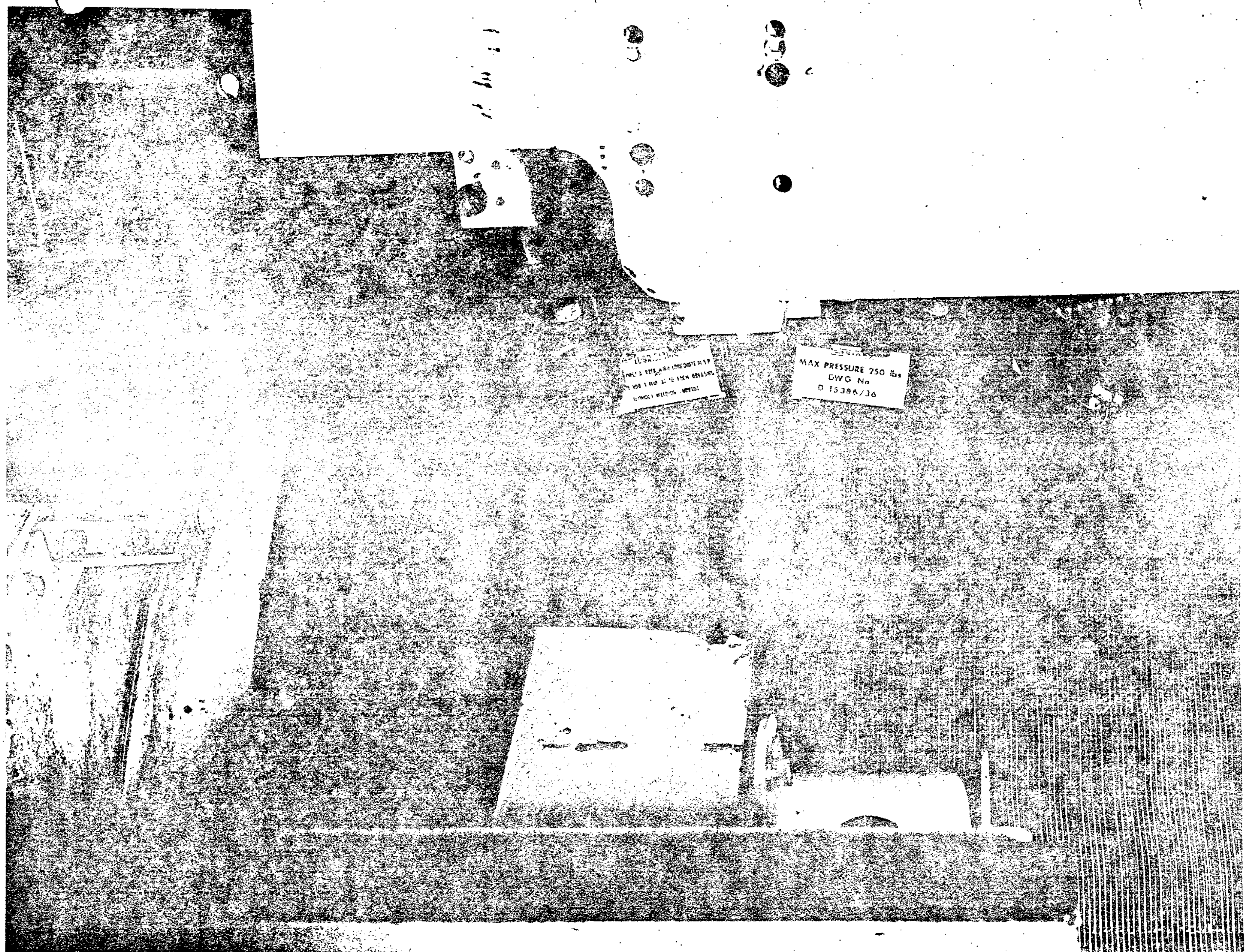



Figure 6. RECUPERATOR INNER AND OUTER JOINT RESISTANCE WELDER

## 1.2. Description of Production Recuperator Manufacturing Facility.

Over the years, these two resistance welding systems, one for the hole joints and one for the inner and outer peripheries, were developed and refined. An automated recuperator line based upon them is now in operation. Sheet metal enters the line in coils of the proper width, and first passes through a multistation press where it is formed and punch dies make the required cuts. The plates then pass through conveyorized stations where they are cleaned to remove press lubricants and inspected for pin holes.

The plates are then stacked in pairs and pass through one of two resistance weld dial feed machines where the hole edge joints are welded. Each of these machines consists of a 10 foot diameter main rotating table with a 5 foot diameter center hole. On this main table are eight resistance welders and a load/unload station. These machines weld the edges of a pair of air holes as seven distinct operations, each done on a separate resistance welder. The eighth is a spare. In operation, a plate pair is loaded on a station each time the main table indexes. This occurs once for every time the individual stations index ten times. There are ten hole pairs per plate and in this way, the seventy individual welding operations (ten hole pairs times seven operations) are performed as the individual stations are indexed from welder to welder.

Each of these dial feed machines is controlled by its own mini-computer. This controls all operations and signals for operator intervention when it is required, either because a fault has been detected or for routine maintenance, such as to change electrodes.

Once the plate pairs are joined around the holes, they are stacked on pallets and transferred to the machines which weld the inner and outer joints. There are five of these machines, each computer controlled. The computer indexes the electrodes between joints, compensates for joint location variations during welding, and monitors the welding process itself to detect electrode wear.

Finally, the completed cores are pressure tested and assembled into the outer exhaust housing before engine assembly.

## 1.3. Summary of Laser Welding Program.

The dial feed machines which weld the hole periphery joints are expensive to operate because of the power, water, and copper electrodes required by the 16 resistance welders which comprise them, as well their labor requirements. Although they perform adequately, their complexity and large number of sliding electrical contacts and bearings complicate their maintenance. Therefore, this program was conducted to develop a laser welding facility to eventually replace them.

The equipment sought had to be capable of welding at high speeds because of the great length of weld joints per assembly. The system had to be capable of precise tracking of the irregular joint geometry at this high speed. The power requirements dictated the selection of a carbon dioxide laser. No other laser medium allows the continuous outputs required.

There are two approaches to tracking complex joint shapes with lasers; either the part and the required holding tools are mounted on a computer controlled two-axis table and moved under a stationary beam, or the beam is swept around a stationary part by a moving mirror system. The mirror system has important advantages for applications such as this. If the stationary beam approach is used, the required indexing table and holding tools are quite heavy and their mass greatly complicates the X and Y axis table drives. The resulting inertia in the system would make tracking of the joint around the small corner radii with the required speed and precision impossible. For these reasons, it was decided that this program would concentrate on the development of a computer controlled moving mirror system integrated with a carbon dioxide laser for the application.

The program was conducted in two phases. In Phase I, begun in 1977, a survey of then available moving mirror laser systems was first conducted. This led to the procurement of a two kilowatt constant wave system with a two axis computer controlled moving mirror from British Oxygen Corporation (B.O.C.).

This was one of the earliest of such systems built. Its development provided valuable experience in the coupling of computers to laser systems as well as demonstrating the feasibility of this approach to recuperator welding and defining the basic tooling concepts and requirements.

This system eventually reached a satisfactory level of reliability for a development facility but did not have the simplicity and ruggedness required of a high volume production machine.

Phase II began early in 1980 with another evaluation of laser welding systems then available. Three manufacturers, in addition to B.O.C. were now found to be building systems which might be suitable for the recuperator application. These three manufacturers were each given an opportunity to make demonstration welds with their equipment and submit proposals for participation in the program. Based on their submittals, a second source, Coherent Incorporated, was selected to join the program in addition to B.O.C.

The goal of Phase II was a production suitable, computer controlled laser welding facility for joining recuperator plate hole periphery joints. Detailed investigation had shown that such a system, although not yet available, was within reach of the present state-of-the-art. Therefore, prototype systems were assembled in both equipment manufacturers' applications laboratories to perform the development work needed before a production system could be designed. This eventually led to the voluntary withdrawal of B.O.C. from the program because of technical problems in the design of holding tools, and integration of the tools with the rest of the system, and excessive distortion of the welded plate pairs. Development of the laboratory system was successfully completed using Coherent Incorporated equipment. Over 800 pairs of plates were joined using this pilot plant system. These plates were used for various tests and to fabricate two complete recuperators, one of which was successfully engine qualified. A production system was then ordered from Coherent, Inc. While it was being built, one of the two production tooling packages required was installed in the applications laboratory facility and run to thoroughly test it. Eight more cores were made in this pilot facility. The first of these was also used for qualification engine testing. After assembly of the complete production system at Coherent, it was acceptance tested by making the plates for five more cores and sent to the Lycoming plant at Stratford. There it was integrated into the recuperator production line (Figure 42) and qualified for production. It is now operating, as a production facility, in the recuperator production line.

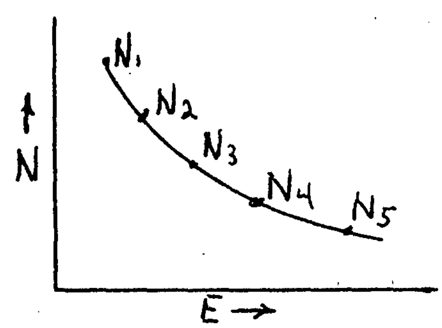
## 2.0. ANALYSIS AND COMPARISON OF LASER SYSTEMS

### 2.1. Theory of Operation of Gas Lasers.

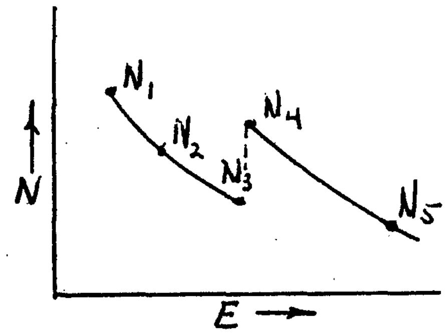
Gas molecules have energy modes: rotational, vibrational and electronic. The rotational mode involves the motion of the molecule about its axis as it moves through space. The vibrational results from changes in the configuration of the molecule as the atoms which comprise it move in relationship to each other within the constraints of the valance forces which hold the molecule together. The third mode, the electronic, results from the energy levels occupied by the electrons within the molecule. All of these energy modes are quantized, only certain discreet energy levels (quanta) are permitted.

A given system of gas molecules contains, at any given instant, different numbers ($N_1, N_2, \ldots, N_i$) of molecules occupying the various permitted quantum levels ($E_1, E_2, \ldots, E_i$). At equilibrium, the distribution of molecules between the permitted states will be the statistically most probable; there will be more molecules in a lower energy state than in any higher energy state. The Boltzman distribution law states that the numbers of molecules in the energy state populations will decrease exponentially with increasing quantum levels (Hamill, 1959).

It must be understood that the equilibrium within a gaseous system is a dynamic one in which vast numbers of molecules are constantly transitioning between the various energy states. The number of molecules in a given energy state describes not a static number but a constantly changing population of size, $N_i$. Thus, at any given instant at equilibrium $N_i > N_{i+1}$ (Anderson, 1976). A plot of population versus energy level of the molecules has this shape:




If, however, this equilibrium is disturbed by an electrical glow discharge into the gas, or by a very sudden temperature change, it becomes statistically possible to have more molecules occupying a higher energy state than a lower. That is, to have a population inversion in which $N_{i+1} > N_i$.




This statistical quantum condition is essential to the operation of all lasers.

In gas lasers, population inversion is accomplished by introducing high energy electrons into the gas from a glow discharge. The electrons collide with gas molecules, exciting them to higher energy states. When these molecules return to lower states, the energy originally acquired from the electrons is released as photons of light of a characteristic wave length. A gas laser is, therefore, a device for converting electrical glow discharge energy into coherent light of a specific wave length. It requires a molecular energy state population inversion to have sufficient gain to reach the threshold for operation.

Carbon dioxide is used as a lasing medium because its linear, symmetrical molecular configuration results in quantum levels which give it comparatively good lasing efficiency. When a molecule at the lowest energy state, the ground level, is excited by collision with a higher energy particle, it can transition to a number of higher rotational and vibrational levels. For purposes of explanation, these can be considered as two levels; an intermediate and upper. Laser action occurs as the excited molecules drop back to the intermediate from the upper level with the energy difference released as a photon of infrared light of wave length 10.6 micrometers. Unfortunately, molecules at the intermediate level cannot be excited to the upper level without first returning to the ground state. The energy of this step is released not as light but as heat.

During the development of carbon dioxide lasers, ways of enhancing these actions were discovered. It was found that if the carbon dioxide was mixed with nitrogen and helium, laser efficiency was improved. Electrical glow discharge is not quantized and excitation of $CO_2$ by it is relatively inefficient. The nitrogen molecule, because of its configuration, is a better acceptor of electrical energy than $CO_2$. It has a number of excited energy levels quite close to those of the upper $CO_2$ levels, and readily transmits this energy to the $CO_2$ molecules. Helium facilitates the return of $CO_2$ molecules from the intermediate to the ground state by accepting the kinetic heat energy of this transition through collisions with $CO_2$ molecules.

## 2.2. Design of Industrial Carbon Dioxide Laser Systems.

The conditions necessary for efficient laser action are the basis for the designs of industrial $CO_2$ lasers. The essential component of all such systems is a gas filled container, called the cavity, equipped with electrical glow discharge electrodes and with mirrors arranged to form a resonator. The laser light leaves the cavity as a beam. Also required is equipment to remove the waste heat given off by the intermediate to ground state transition. A method for either changing the laser gas or filtering and recycling it is required to remove the contaminants generated by the disassociation of $CO_2$ and $N_2$ by the excitation discharge.

## 2.3. Laser Systems Evaluated in this Program.

The B.O.C. Laser System , the system originally procured in Phase I of this program uses four glass tubes connected in series to form a laser cavity seven meters long (Figure 7). In order to shorten the machine, these tubes are arranged in a horizontal U, the base of which is an assembly of two $45^{\circ}$ 100 percent reflecting mirrors. One end of the U has a 100 percent reflecting mirror set normal to the tube axis. The other end has an output window of optically flat gallium arsenide coated to have a reflectivity of 35 percent to 10.6 micron light. This provides the resonant optical cavity which causes the lasing action to produce a light beam oriented in the direction of the cavity's axis.

There are four anodes and two cathodes which conduct the glow discharge through the gases. If the glow discharge converts to an arc, insufficient energy is transferred into the laser gases and the population inversion is lost. If this occurs, the resultant current flow loads down the high voltage system and circuit breakers in the system are tripped, shutting down the laser. In order to increase the stability of the discharge, turbulent flow of the gases in the tubes is required, and this is provided by the design of the gas inlet nozzles located at the anodes.

The laser operates at a gas pressure of 30 to 35 torr. There is a mechanical vacuum pump used to evacuate the system at initial start up and then, after the system has been back filled with the gas mixture, a Roots blower is used to circulate the laser gases during operation.

In the circulation loop with the laser tubes are heat exchangers which extract the waste heat given off as the $CO_2$ returns to the ground quanta state, and a number of gas filters. These filters remove oil droplets and water vapor as well as the oxides of nitrogen, and the oxygen and carbon monoxide caused by

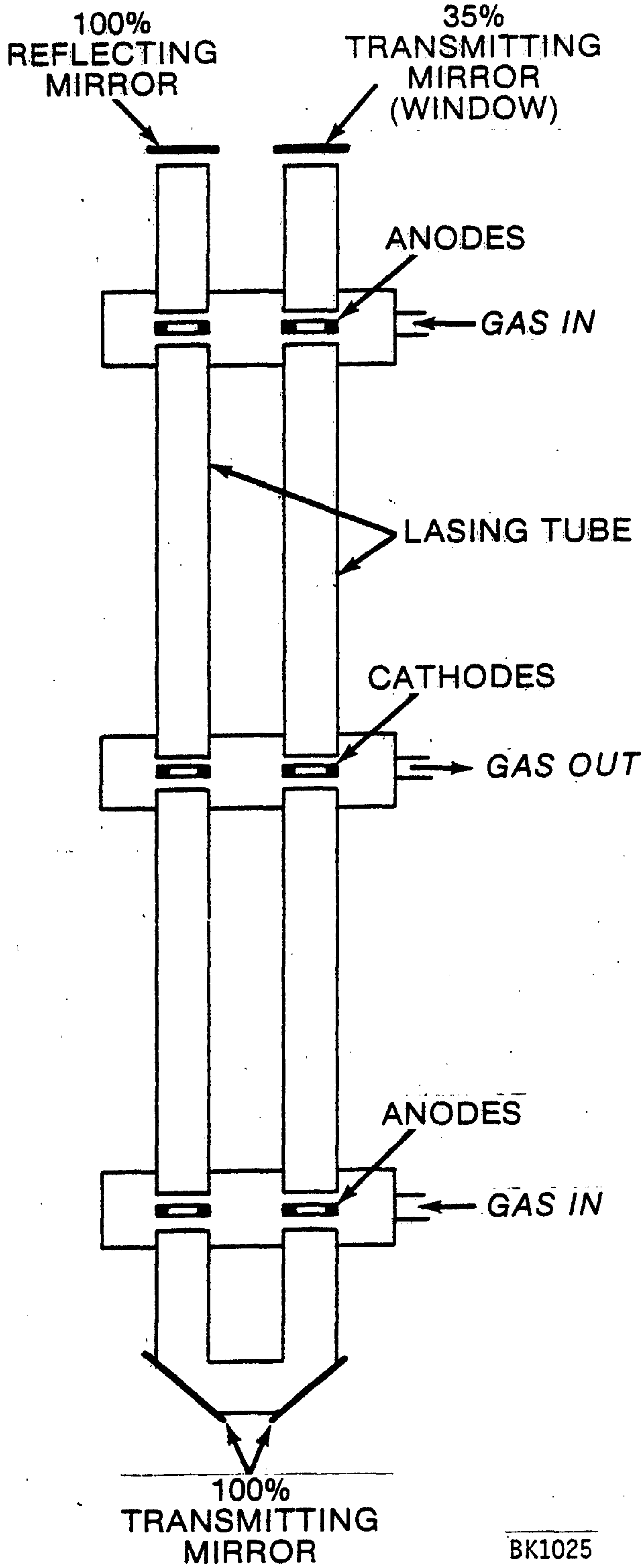



Figure 7
B.O.C. LASER CAVITY

disassociation of the laser gases. There are also gas mixers and a system for adding gases to replace losses. All gas flows through the various parts of the system are controlled by solenoid operated valves.

Cooling water must be provided to numerous parts of the system. Besides the gas heat exchangers, the mirrors, electrodes, vacuum pump, output window, and the mounts for the gas filter ovens are all water cooled. There is a water cooled calorimeter which acts as both a beam metering device and as a power dump. The welding beam is deflected into this calorimeter by a moving mirror in this system, rather than shutting down the laser to turn off the beam.

The beam path is aligned and the weld joints are tracked while developing control computer programs by a small helium neon laser mounted next to the main laser's output window. A prism device deflects the HeNe laser down the main laser output path.

All of the components described thus far are built into one assembly (Figure 8). The assembly has a frame of steel I-beams to provide a rigid bed to maintain the very precise alignments required between the tubes, the mirrors, and the output window. Even the smallest change in alignment of these components causes the output power to change significantly.

The power supply which provides the glow discharge power is housed in a separate cabinet (Figure 9), which also houses the gas regulators and vacuum pump controls. The power supply consists of four identical circuits, each of which supplies power to one anode. The cathodes are at ground potential, and the potential difference between them and the anodes is about 24 kilovolts. The discharge current flowing in each tube is monitored by a separate milliampere meter. The output of the laser is controlled by this discharge current. There is, however, a minimum value required to maintain glow discharge, and this gives a laser output of about 800 watts. Below this, the laser will not operate. The power system is, therefore, an open loop system. There is no pulsed operation capability, although it is possible to ramp power between the 800 Watt base output and the set welding power in order to eliminate the end weld holing that can result from square wave beam shut off.

The machine produces a columnar light beam which has power distributed across its cross section in the $TEM_{00}$ mode. In this Gaussian distribution, the highest energy is in the center of the beam and decreases exponentially from the center. The beam from this laser can be focused to a spot .008 inch (0.2 millimeters) in diameter by the 75 millimeters output lens used with it. The machine is, therefore, capable of producing a maximum power density (when operating at its 2,000 Watt constant wave maximum output) of $6.4 \times 10^6$ watts/centimeters$^2$.

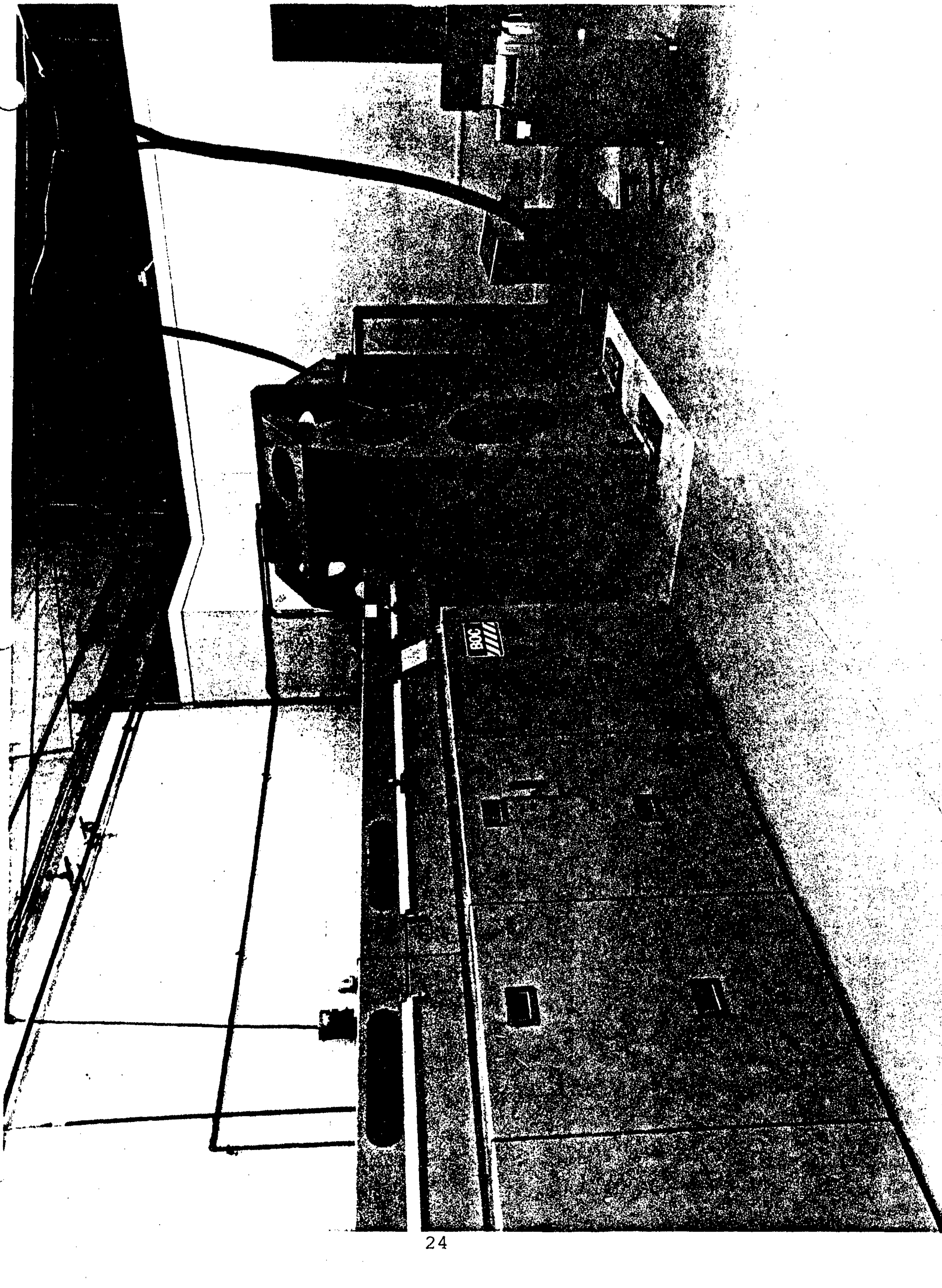



Figure 8
BRITISH OXYGEN CORP LASER MACHINE

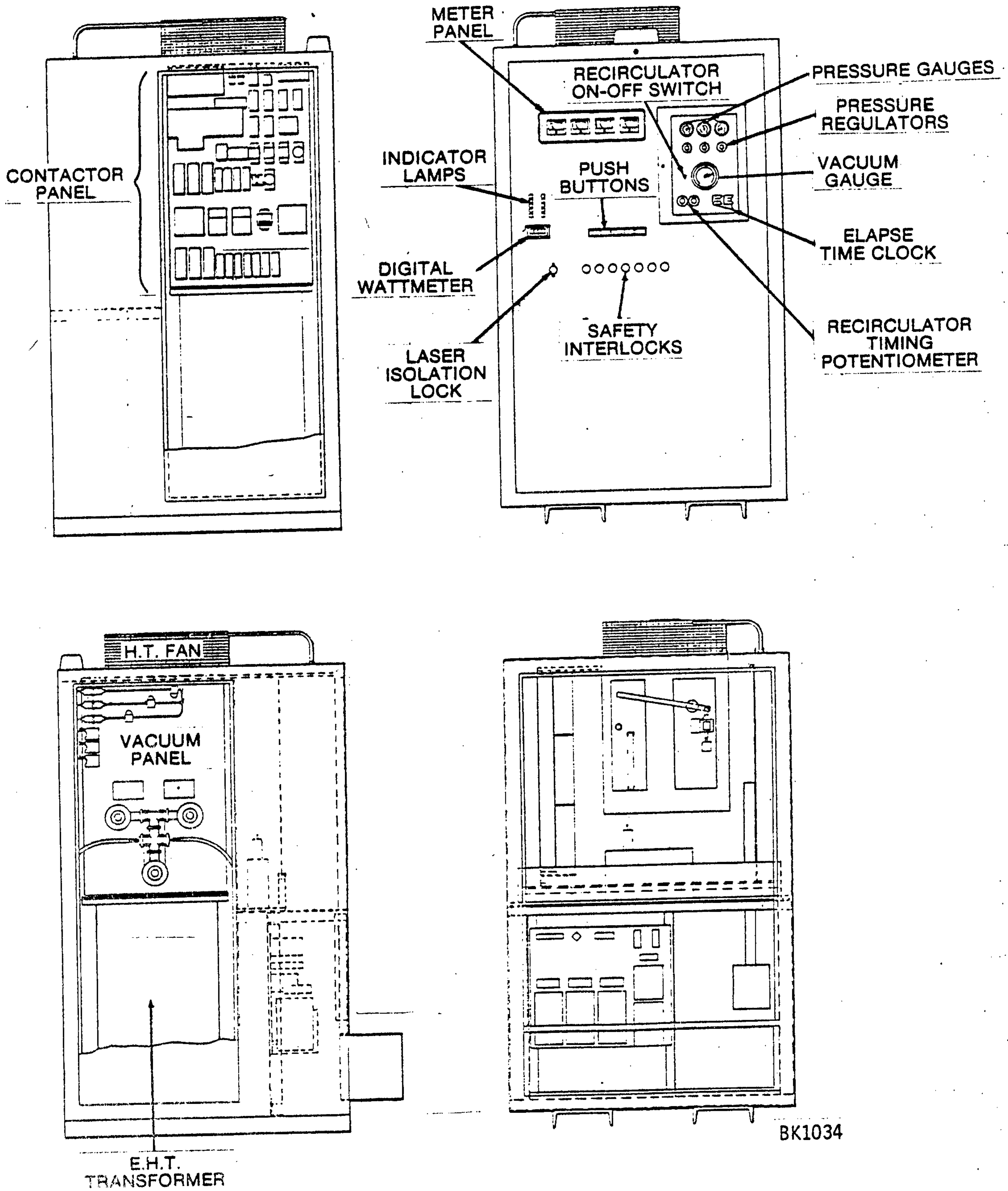



Figure 9
BRITISH OXYGEN CORP POWER SUPPLY

The welding development work done in Phase I showed three major design deficiencies with this system: laser output instability, design deficiencies in the high voltage system, and the unsuitability of helium neon lasers as aiming and alignment devices for $CO_2$ moving mirror laser welders.

Daily operation of the system showed it to require almost constant realignment of the output window and frequent alignment of the various cavity mirrors. This resulted from the basic design of the machine itself. The machine bed which supports the cavity is almost 13 feet (4 meters) long, and is made of steel I-beams. Small temperature variations in beams of this length cause dimensional changes far in excess of the tolerance of the system to misalignment. Because of these changes, output variations of over a hundred watts in a few minutes were not uncommon. Alignment of the window and mirrors is done by turning screws located inside the metal safety covers of the system. This requires that the safety interlocks, which shut down the laser when the covers are opened, be defeated with a special key. This is undesirable in a laboratory system, and completely unacceptable in a production system.

Numerous problems with the high voltage system were encountered, although most were solved by redesign and retrofits done by the manufacturer. Basically, these sometimes spectacular failures were caused by the entire laser glow discharge current being shunted through the control meters, and to many of the components which were, at best, marginal for the electrical power involved. Even when operating dependably, this type of high voltage system is not suitable for production laser applications. This open loop system provides no compensation for power drift, either from changes within the high voltage generating components, or in conditions within the laser cavity. This control is provided by the operator observing the output calorimeter reading and making compensations as required. This operator dependence is unacceptable in a high volume production machine. Because the calorimeter operates only while the system is not welding, there is no compensation or control while the system is actually joining parts. For recuperator joint welding with its short cycle time to weld each joint, this might be acceptable, but for many other production applications, it would not be.

The B.O.C. system could not maintain a laser action below about 800 watts because the system cannot maintain a glow discharge at power input currents below that required for that output. Start-up of the system at the beginning of the work day, or after discharge is lost for any reason, is quite complex and time-consumming. So, once operating, the laser itself is not turned off. The welding beam is turned off by dumping the laser output into a calorimeter. For most welding applications, where loading, unloading and positioning may be 50 percent or more of the welding cycle, this is very inefficient.

The helium neon laser supplied with this carbon dioxide laser for both beam path and weld track alignment, was not, in practice, adequate. This small laser (0.95 Miliwatt) produces light at 632.8 nanometers. It is installed because it is visible and harmless if it hits a person. This is in marked contrast to the invisible output of the carbon dioxide laser which could cause severe injury. A rotating prism aligns the beam from this laser so it passes through the output path of the main laser while the main laser is deflected into the calorimeter. In this way, it is intended to be used to align the various mirrors in the light path to the work-piece and to track and align the beam path on the work-piece.

The system is much more attractive in theory than in practice. It is adequate only for providing very rough mirror alignment. One can only determine its impact location on a given mirror by looking squarely at that mirror, because of paralax. In order to do this, one's head must be in the beam path, blocking the laser. So, in practice, alignment is made by firing the main laser at pieces of asbestos board downstream of each mirror and using the 0.6 inch diameter columnar beam's symmetry to align the mirror. It is not possible to do this with the HeNe laser because its beam is only about 0.1 inch in diameter and will only mark photo-sensitive paper because of its very low power.

The helium neon laser is useless for alignment of the tooling, beam track and work-piece, which is critical to this and most welding applications. The acute viewing angle and the high welding speed means that alignment can only be evaluated by marking the part with the $CO_2$ laser.

## 2.4. Coherent Inc. Laser System.

Coherent Inc. was included in the program early in Phase II because a preliminary evaluation showed it had significant design advantages over the early B.O.C. system. The Coherent laser has 48 feet of glass tubes which form the cavity arranged in a W with two cathodes and one anode per tube. The glass laser tubes are mounted within larger glass tubes, and the annulus thus formed is part of an elaborate system for controlling system temperature and thus maintaining output stability. The tubes are mounted on a support structure (Figure 10) which consists of cast iron end plates and laminated micarta standoffs bonded to an outer steel tube and inner plastic tube approximately the same length as the laser tubes.

When the laser is in operation, dielectric oil flows through the outer passages of both the laser tubes and the support structure tubes. This oil is passed through a heat exchanger/heater which keeps the entire laser cavity assembly within $\pm$ $0.1^{o}$ Fahrenheit.

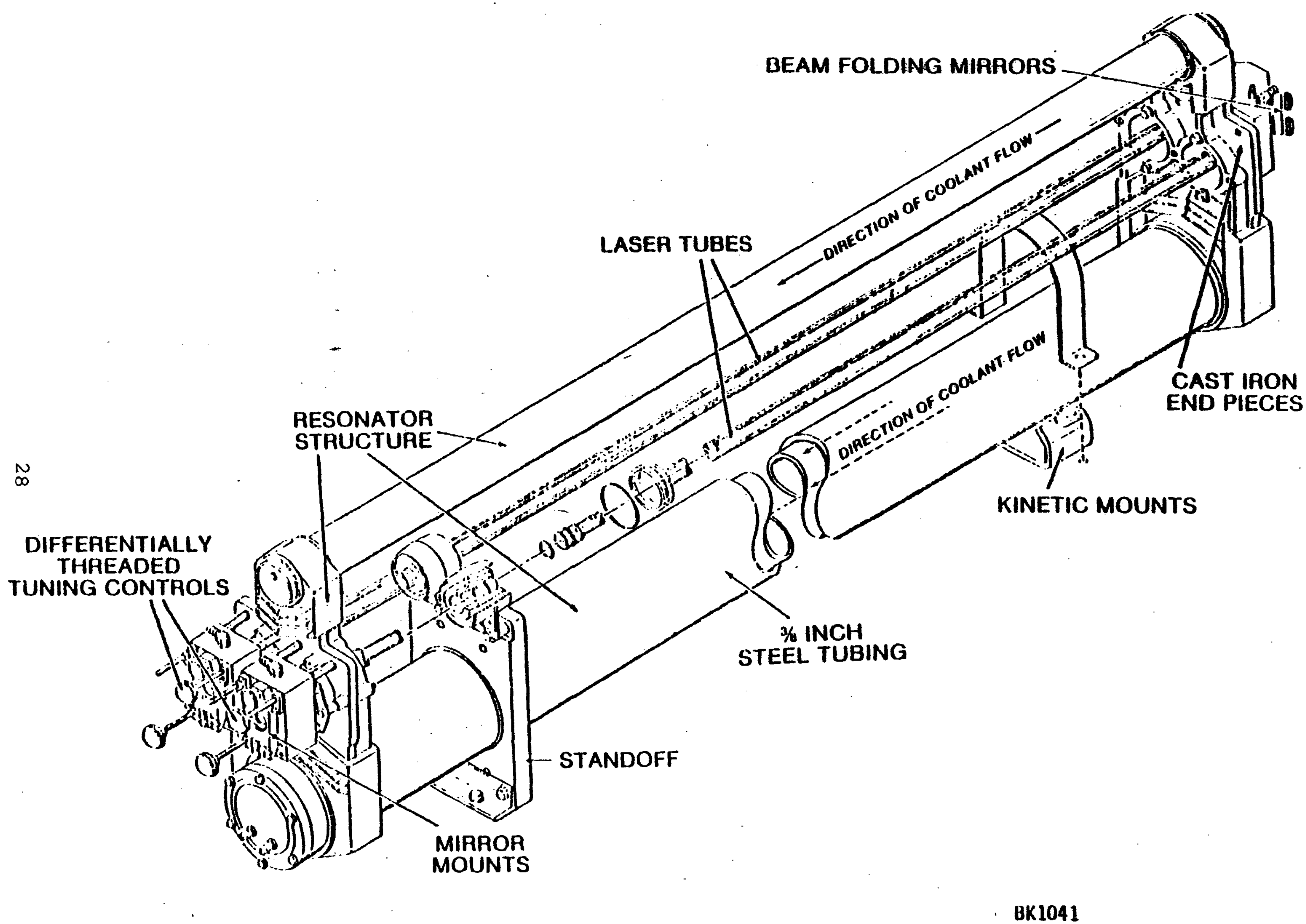



Figure 10
COHERENT INC LASER CAVITY AND RESONATOR STRUCTURE

The laser uses 100 percent reflective mirrors set at the blank end and corners of the cavity and a 27 percent reflective gallium arsenide window at the output end. The system uses a mixture of 13.5 percent nitrogen, 4.5 percent carbon dioxide and 82 percent helium at a pressure of 20 Torr. Gas leaving the discharge of the laser tubes is pumped to atmospheric pressure and passes through an oil trap, a moisture trap, and then over a heated catalyst which recombines the gases disassociated by the glow discharge. This recycled gas, together with a 10 percent by volume purge-flow of new gas, then returns through the center of the support structure to the laser tubes. Passing it first through the support assures that it is temperature stabilized with the resonator cavity and support.

A high voltage DC power supply initiates and sustains the laser glow discharge (Figure 11). Power triodes, connected in series with each discharge anode-cathode pair provide current regulation and modulation. Appropriate control circuitry using voltage and current feedback from current regulators adjusts the high voltage via magnetic amplifiers as required by the discharge and power dissipation limits of the triode regulators. These signals are also used to limit average discharge current to 50 milliamperes per anode-cathode pair.

There is a gold-plated reflective shutter which when closed reflects the beam into a water-cooled dump. This permits operating the laser for set-up, calibrations, set, without having the beam pass through the out-put mirrors. However, it is not normally used as a working beam on/off switch. Because the system has a closed loop and quick response power supply, the power supply is used to turn the beam on and off and to provide the power variation which results in pulsed laser output.

This power supply is capable of sustaining operation at or below 50 watts of laser output, so the $CO_2$ laser can be used for alignment. In practice, a cross hair grid is placed in the beam path downstream of each mirror, and then the laser, at low power, is fired onto an infrared-sensitive card held downstream of the grid. The symmetry of the cross hair in the pattern is used to align the mirror. No auxiliary alignment laser is needed or fitted. Alignment of the welding beam with the tooling is done with a low power slow pulse, so that the laser burns a series of tiny holes in a piece of paper set on or in the welding tools. This permits very precise set-up alignment of the complete system. This laser, like the B.O.C., produces a $TEM_{00}$ mode, but it has a maximum constant wave output of only 525 Watts. However, in the pulsed mode used in this program, instantaneous peak power of about 2,500 watts is possible.

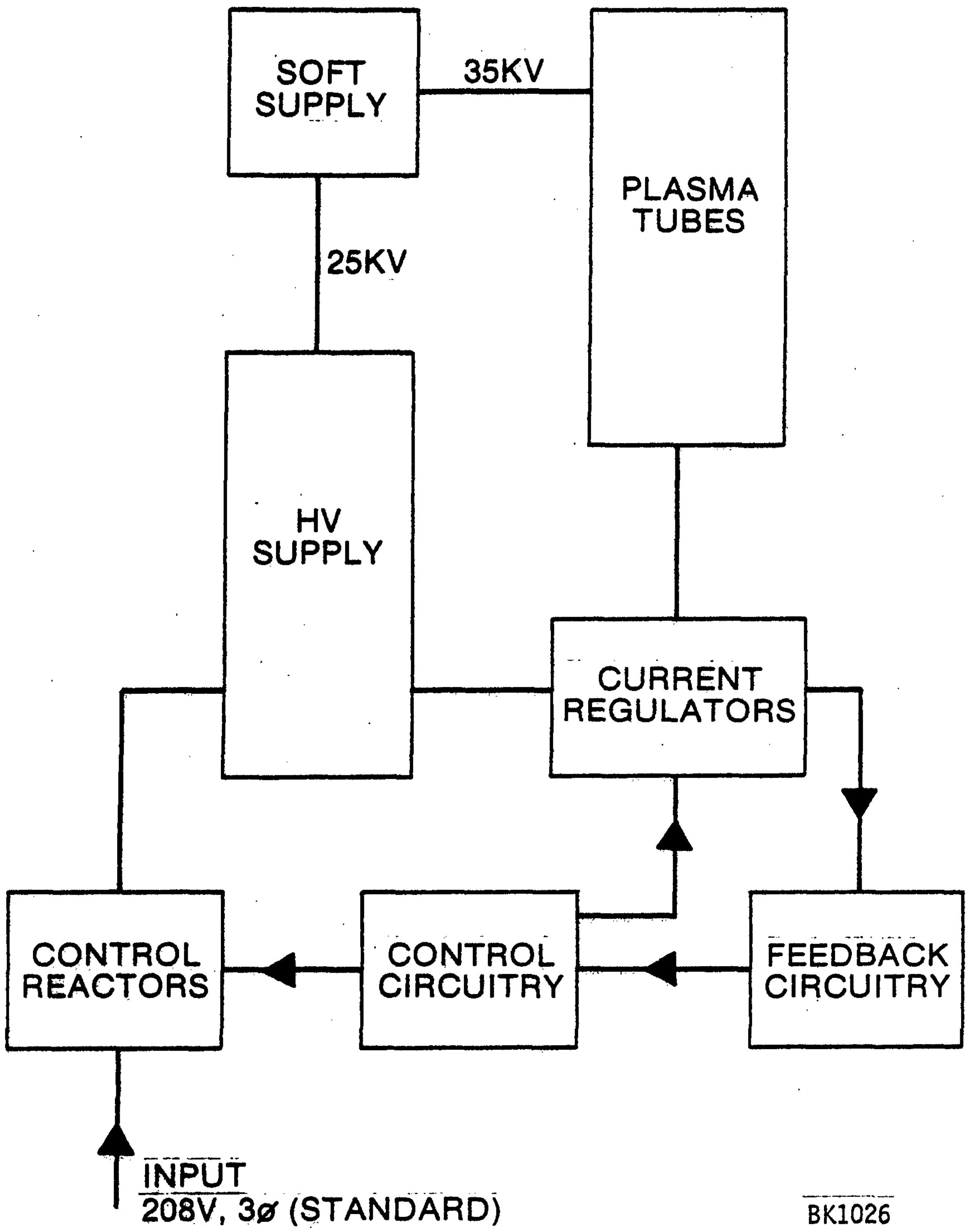



Figure 11
COHERENT INC POWER SUPPLY BLOCK DIAGRAM

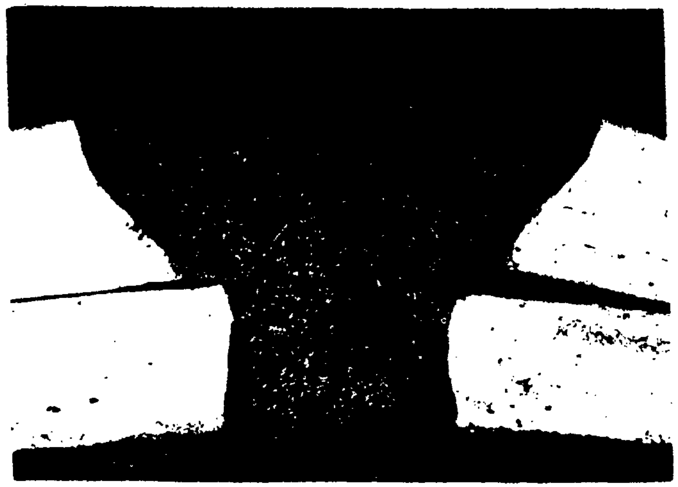
2.5. Comparison of Laser Systems

The B.O.C. System was of an earlier generation than the Coherent System and has a number of design deficiencies which do not make it suitable for production welding of recuperators. Plate pairs were successfully joined with it, however, using about 1,600 watts of constant power at 235 inches per minute (100 millimeters per second) welding speed. With these settings and hole side tooling, as described below, 25 plate pairs were joined, as part of the selection process for a vendor to build the production system. These joined plates were intended to be resistance welded on the outside and inside to test their compatibility with the existing production system, and then pressure tested. They were found to be so badly distorted that it was not possible to resistance weld the edges. This was the problem which led B.O.C. to withdraw from the program after successfully solving so many others.

Coherent, Inc. successfully welded a similar pack of 25 plates which were readily resistance welded. The plates were less distorted than those welded around the hold peripheries by the current dial feed resistance welders, which are themselves less distorted than the B.O.C. welded plates. The Coherent laser welds, although metalurgically very similar in cross section to the B.O.C. welds, (Figure 12), were made at about 360 Watts root mean squared pulsed power at 85 inches per minute (38 millimeters per second). Pulses were 1.5 milliseconds long at 180 Hertz.

The difference in distortion is readily understood when the energy input in Joules per millimeters of weld is calculated. The B.O.C. welds were made with about 16 Joules per millimeter while the Coherent, Inc. welds used only about 9 Joules per millimeter. The recuperator plates have high residual stress caused by the forming process, and the excess heat input of the B.O.C. welds undoubtedly locally relieved more of the stresses than were relieved by the lower heat input of the Coherent welds.

Various Coherent Systems were used to weld about 4,500 recuperator plate pairs during this program. This is over 20 miles of weld and 45,000 on/off cycles of the lasers. The lasers operated with flawless dependability with no operator adjustments after the initial set-ups had been made. This was in marked contrast to the early B.O.C. laser which, once a number of design deficiencies had been corrected, operated dependably but still required frequent operator adjustment of the output window and mirrors to maintain output power stability.




B.O.C. WELD


COHERENT WELD

Figure 12

CROSS SECTIONS OF RECUPERATOR LASER WELDS

BK1038

## List of References

Anderson, J. 1976. Gas Dynamic Lasers. New York: Academic Press.

Hamill, W. and Russell, R. 1959. Principles of Physical Chemistry, Englewood Cliffs, N.J.: Prentice-Hall, p. 567-9.

## 3.0. ANALYSIS AND COMPARISON OF COMPUTER AND MOVING MIRROR SYSTEMS

### 3.1. Introduction.

A number of discrete functions must be controlled by the computer in the production recuperator laser facility, as shown in Table 1. During the development phases of this program, the load, unload, and index functions were performed manually, because they are very slow compared to a computer's processing time to control them, because they were considered technically trivial, and to reduce the cost of experimental tooling.

The basic problems of computer control of this process are the tracking of the beam along the joint, and turning the laser on and off at the correct instant. Both systems investigated provide closed loop control of the moving mirror position and velocity, but neither system provides closed loop computer control of the laser welding parameters. This was considered unnecessary because both laser systems investigated were supposedly stable enough to operate without outside parameter control.

It would, therefore, appear that the integration of the laser and the computer involves connecting a circuit no more complex than that used for an indicator lamp so the computer can turn the laser on and off as required. This is the case only in theory. As explained in Section 2.0, industrial $CO_2$ lasers are complex electrical and electronic machines, involving both power and control circuits for pumps, heaters, coolers, catalyst ovens, gas and water solenoids and the high voltage for the laser cavity. The operation of a device as electrically sensitive as a computer in an environment as electrically noisy as that of a laser, produced unanticipated problems during the development of the B.O.C. systems. Others (Strait, 1977) have encountered similar problems. The cause of the erroneous signals which plagued the system's development, and which were usually misidentified as program faults, is shown in Figure 13. An electrical circuit through ground was completed between the laser and the moving mirrors by the aluminum tube used to enclose the laser path. Through this path, extraneous signals entered the computer feed back circuit. Once the problem was identified, the solution was obvious: place a short length of non-conductive tube in the beam path shield. Unfortunately, many hundreds of hours were spent on the problem before the cause was discovered by the B.O.C. engineering staff.

The computer control of the actual welding portion of the cycle, and the indexing between the two holes welded as a pair, involves the precise tracking of the laser beam around the joint as well as on/off control of the beam. This tracking is done by controlling the position and velocity of two tables upon which are mounted the two mirrors that reflect the beam to the work-piece through the

TABLE I

RECUPERATOR WELDING COMPUTER CONTROL FUNCTIONS

| No. | Function | Production Facility Device | Production Facility Closed Loop? | Development Facility Device | Development Facility Closed Loop? |
|---|---|---|---|---|---|
| 1 | Load A Plate | Load/Unload Arm | yes | Manual | --- |
| 2 | Load B Plate | Load/Unload Arm | yes | Manual | --- |
| 3 | Position Plate Pair on Hold Fixture | Hold Fixture | yes | Manual | --- |
| 4 | Close Holding Fixture | Hold Fixture | yes | Manual | --- |
| 5 | Start Gas Purge | Gas Solenoid | no | Manual | --- |
| 6 | Check Mirror Home Position | Moving Mirror System | yes | Moving Mirror System | yes |
| 7 | Start Travel Along Weld Path | Moving Mirror System | yes | Moving Mirror System | yes |
| 8 | Turn On Laser | Laser | no | Laser | no |
| 9 | Control Beam Direction/Velocity | Moving Mirror System | yes | Moving Mirror System | yes |
| 10 | Turn Off Beam | Laser | no | Laser | no |
| 11 | End Weld Travel | Moving Mirror System | yes | Moving Mirror System | yes |
| 12 | Index to 2nd Shape | Moving Mirror System | yes | Moving Mirror System | yes |
| 13 | Start Travel Along Weld Path | Moving Mirror System | yes | Moving Mirror System | yes |
| 14 | Turn On Laser | Laser | no | Laser | no |
| 15 | Control Beam Direction/Velocity | Moving Mirror System | yes | Moving Mirror System | yes |
| 16 | Turn Off Beam | Laser | no | Laser | no |
| 17 | Turn Off Gas Purge | Gas Solenoid | no | Manual | --- |
| 18 | Open Holding Fixture | Holding Fixture | yes | Manual | --- |
| 19 | Index Table to Next Hole Pair | Index Table | yes | Manual | --- |
| 20 | Repeat Steps 3 through 20 Nine Times | --- | --- | ----- | --- |
| 21 | Extract Completed Plate from Hold Fixture and Place on Finished Stack | Load/Unload Arm | yes | Manual | --- |

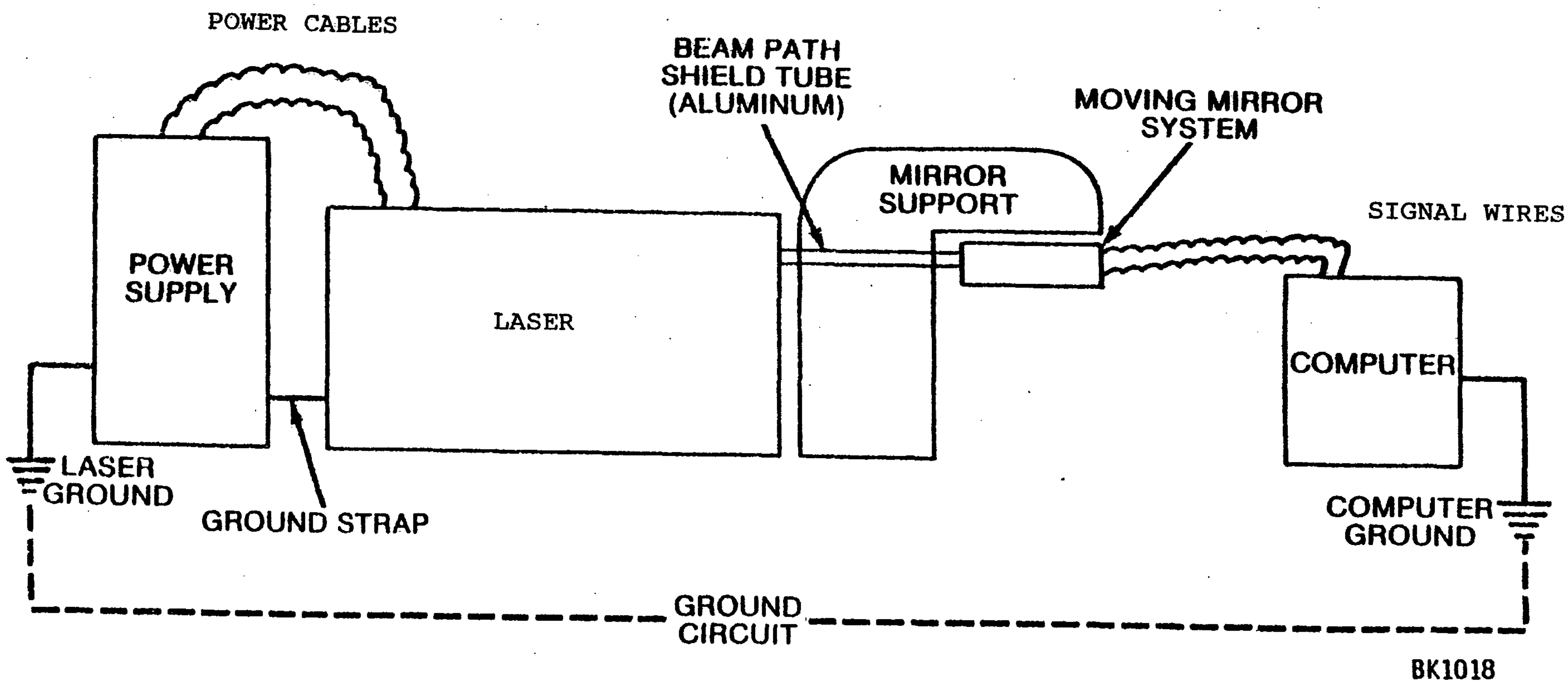



Figure 13

B.O.C. COMPONENT GROUND CIRCUIT

output lens (Figure 14). These X-axis and Y-axis tables are driven by motors which are coupled with feedback signal generation devices: tachometers and encoders. These provide location, velocity, and direction information to the computer.

By following instructions in the program, the computer generates signals to move the drive motors over the required path. Then, based on feedback signals, it must issue correction signals. There are two approaches to this function. One involves realtime calculation of the feedback data to produce an output correction signal. Whether this is possible depends on the velocity of the mirrors, the frequency at which corrections are required, and the speed at which the central processing unit (CPU) and arithmetic logic unit (ALU) can perform these functions.

Another method must be used if real time error correction calculation is not possible in the time available. This method involves first processing the definition of the segments into which each track is divided to generate a list of ideal velocity and displacement data for each segment. These ideal displacement values are then compared with the actual inputs generated during operation. This system simplifies the real time calculation so the CPU and ALU can keep up with them. However, it greatly complicates both the system programming and architecture and increases the requirements for memory capacity and buffering.

3.2. B.O.C. Computer System.

The B.O.C. System was equipped with a Digital Equipment P.D.P. 11/04 which controlled the beam path through the moving mirror system and the laser and shielding gas on/off. This computer uses a 16 bit word and is programmed in ESSI, a European process control language. Input is through a paper tape reader and a mechanical teleprinter. This system does not have sufficient computing power and speed to allow real time calculation of error corrections.

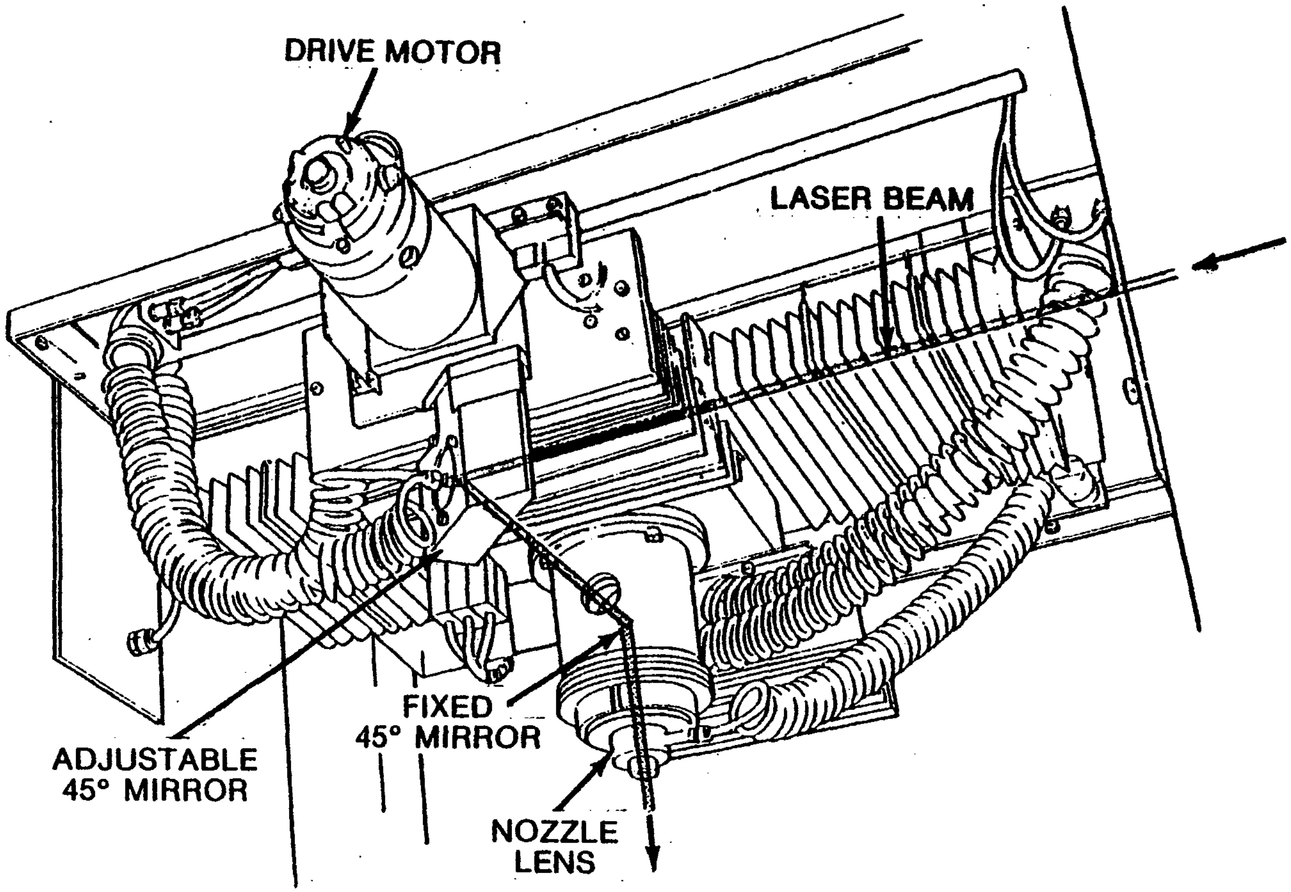
The shapes of the recuperator hole joints can be resolved into a series of circular arcs. The computation of the radius (r) of each arc is $r=\sqrt{(\Delta X)^2 + (\Delta Y)^2}$ and the length of the cord of each segment is calculated by the same method.

The computations of the velocities (V) along the axis are:

$$V_x=s/r\ [\mathrm{SIN}\ ((2n-1)\ \emptyset).\Delta_x + \mathrm{COS}\ ((2n-1)\ \emptyset).\Delta_y]$$

$$V_y=s/r\ [\mathrm{COS}\ ((2n-1)\ \emptyset).\Delta_x + \mathrm{SIN}\ ((2n-1)\ \emptyset).\Delta_y]$$

where (s) is the required beam travel speed, and Ø is one-half the angle subtended by a the chord and the arc of the segment.




BK1033

Figure 14
B.O.C. MOVING MIRRORS SYSTEM

Other computations are required, but these three take most of the processing time. This system was specified to operate at 235 inches/minute with a maximum track error of 0.004 inch. This meant the smallest arcs could be approximated by straight lines 0.027 inches long. The maximum available processing time is the length of one segment divided by the speed, 6.97 microseconds.

The computer has no hardware multiply or divide, and software implementation of these functions is required. Multiplication of two 16 bit words by this system takes approximately 350 microseconds. Division is even slower. The square root function needed to find the radius of curvature and the length of the cord is an iterative process whose time is governed by the starting value and accuracy requirements. It is, however, much longer than the time required by a single multiplication. Because of these time constraints, line by line processing was not possible and the method of precomputing ideal velocity and displacement data was used.

Figure 15 is a functional block diagram of the system. A command table is generated by the input controller and is used by the output controller as its program to control X-Y movement and sequencing of external functions. Each line of the computer program is transposed into a single coded entry in the command table using the following format:

| 15 | 14 | 13 ... 0 |
|---|---|---|
| | | Auxiliary Code |
| 0 | 0 | Vacant |
| 1 | 0 | Straight Line |
| 1 | 1 | Circular Arc |
| 1 | 2 | Auxiliary Code |

The data buffer is loaded by the input controller with the segment definitions for subsequent use by the output controller. Only straight lines are involved because segments of circular arcs are approximated by straight lines. Therefore, only one format for segment definition is required.

Pointer/Terminator
X-axis velocity
Y-axis velocity
x-coordinate
y-coordinate

If the segment is a straight line, the pointer/termination contains a termination code because only one definition is required. If the segment is the chord of a circular arc, a pointer code to the next definition in the arc is given. If it is the final segment of an arc, the terminator code is given.

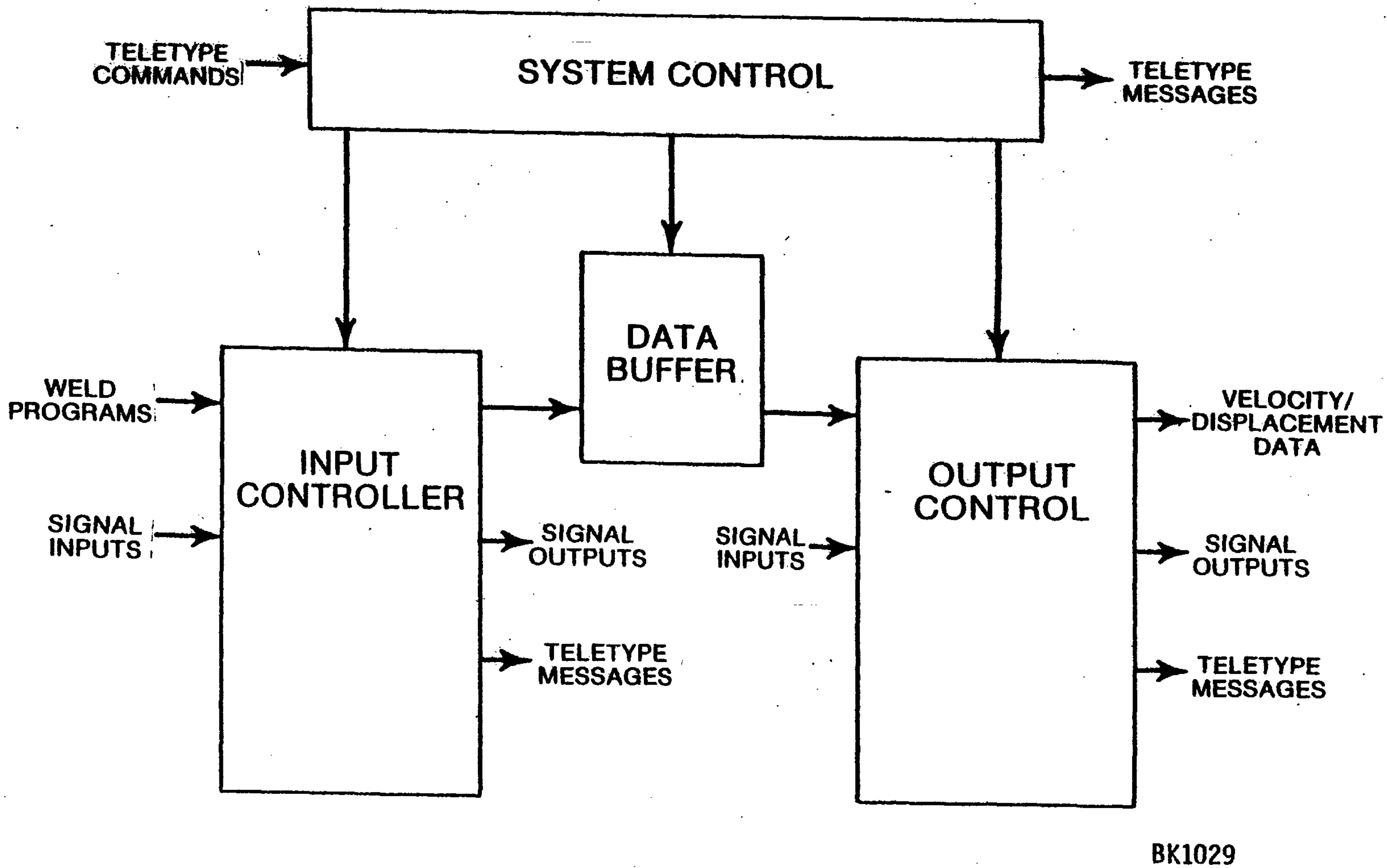



Figure 15
B.O.C. COMPUTER FUNCTIONAL BLOCK DIAGRAM

The output controller receives inputs from the command table which were generated by the input controller, and executes them in sequence to control the welding process. It computes the positional error between the axis feedback data and the segment definitions from the data buffer. It then computes compensation factors which are used to generate compensated velocities and displacements for the next segment section. These are required to compensate for dynamic errors in the mirror motors and drives. It also maintains data on the current location of the axis with reference to the system origin through interrupts generated by the position encoders, and maintains status data on the laser and shielding gas on/off, using data from the device interface.

In addition to these functions, the output controller also maintains the clock upon which all these functions are based because no hardware clock is provided.

The geometry of the laser path initially selected for debugging of software was a straight sided triangle with 0.2 inch radius at each corner (Figure 16). This simpler shape (in comparison to the actual shape of the recuperator hole) was chosen to make identification of programming errors easier.

The first tests of the system indicated an error band of 0.024 inch. The total width of the land on which the weld track and holding tools must fit is only 0.080 inch. Hence, this error band could not be tolerated.

The worst errors occurred on the upper right corner of the triangle joint because here the system tracks a small radius corner involving the most rapid acceleration on one axis and deceleration on the other. In this situation, the effect of a velocity change will not be sensed before the next error calculation is made. This error was reduced by modifying the program to vary the amount of compensation generated, based on the increase in error since the last correction, by pulsing velocity changes toward the desired value, and by taking into account the response time of the axis drive motors.

At this point in program development, the program was rewritten for the actual shape required to weld one pair of recuperator hole joints as a unit with the laser beam and shielding gas commands included. Also included was an abort subroutine which would stop mirror motion, and turn off the beam and shielding gas if an error in excess of a value inputted through the teleprinter was exceeded. This was normally set for 0.004 inch.

When the system was repeatedly cycled with this program to verify its dependability, aborts occurred on about 3 percent of the runs.

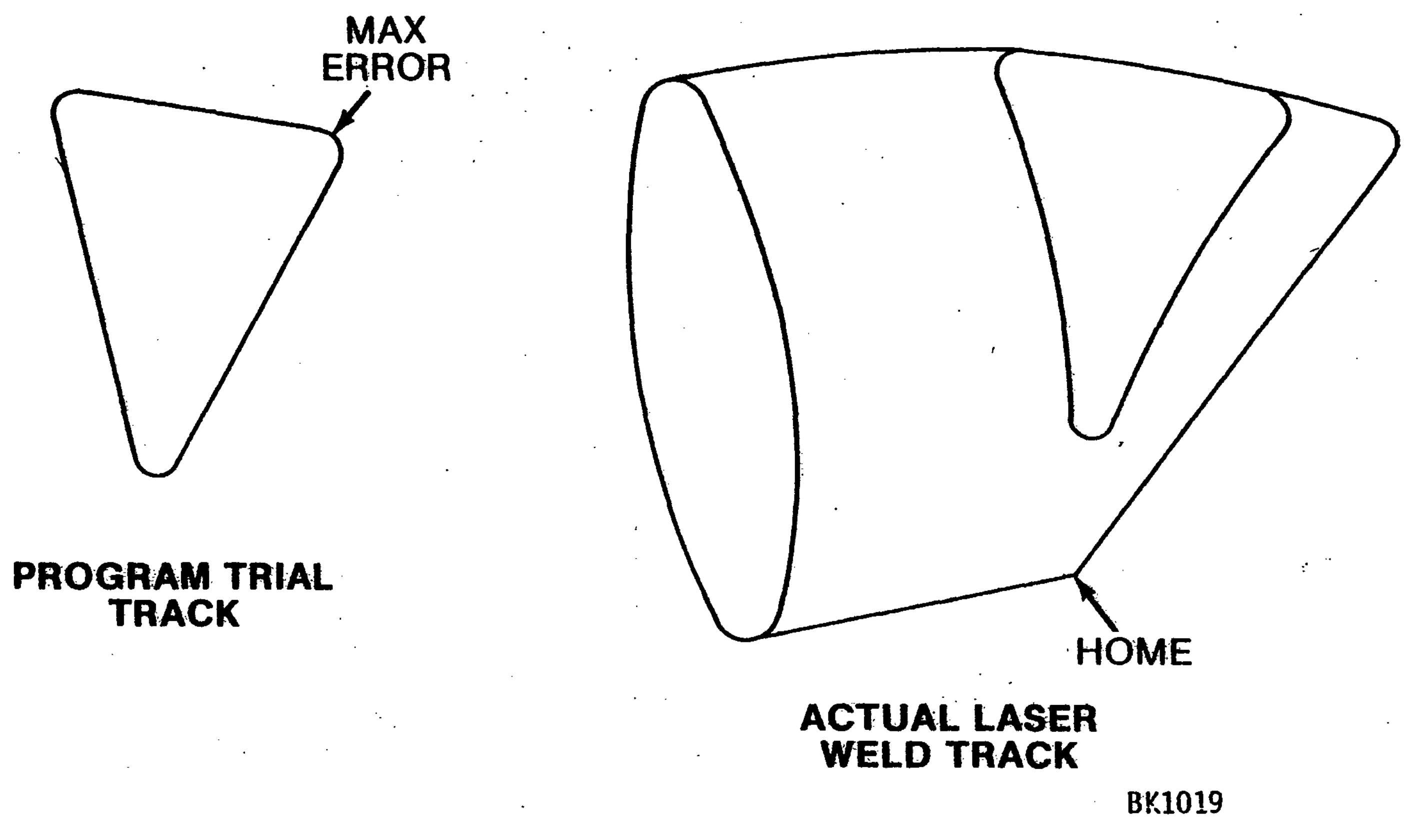



Figure 16
TRIAL AND ACTUAL LASER WELD TRACK
B.O.C. SYSTEM

This was not acceptable. Increasing the set error band did not reduce the percentage of aborts. By using photo-sensitive paper and the helium neon laser and finally, by burning the track into thick plexiglas with the $CO_2$ laser, the repeatability of the weld track was not acceptable.

A great deal of work was done to eliminate these problems. A number of hardware faults were found and corrected. Among them were a defective teleprinter, a loose circuit board contact in the computer and a water hose in the moving mirror system which sometimes caught on a circuit board. This deflected the board and caused it to short circuit against the motor housing. In addition to these intermittent faults, the false signals entering the computer system through the ground circuit, as explained above, made the isolation and solution of software problems very difficult.

However, eventually all these faults were found and corrected and the B.O.C. system was made to operate dependably while tracking the joint shapes at 235 inch/minute, within the required error band.

### 3.3. B.O.C. Moving Mirror System.

The moving mirror system which the computer controls to sweep the beam around the joint shape is shown in Figure 14. The columnated beam from the laser optics enters from the right in the figure and is reflected first from a mirror set at 45° to the beam path about a vertical axis, then from a mirror set at 45° about a horizontal axis. It then passes through a 38 millimeter (1.5 inch) diameter output lens of potassium chloride. This lens has a 75 millimeter (2.93 inch) focal length and is adjustable through a total distance of 20 millimeters (0.78 inch). It is protected from metal vapors and splatter by an inert shielding gas which enters the assembly downstream of the mirror and flows out through the beam orifice (Figure 17).

The mirrors are of gold-plated copper and are water-cooled to avoid the misalignment that could result from heat buildup. The mirror tables are suspended from the slides by a system of linear roller bearings which are driven through a ball screw device by the servomotors. These motors are equipped with tachometer generators and 200 line optical encoders which generate feedback signals for the computer.

The water-cooling system led to a number of problems. Among them were fatigue failure of water lines and fittings and other mechanical problems caused by feed lines and wiring attached to the high speed moving mirrors; for example, the fouling of hoses and wires on encoder boards. As is often the case with high technology devices, most problems were caused by simple mechanical design which was given insufficient attention because it was considered trivial.

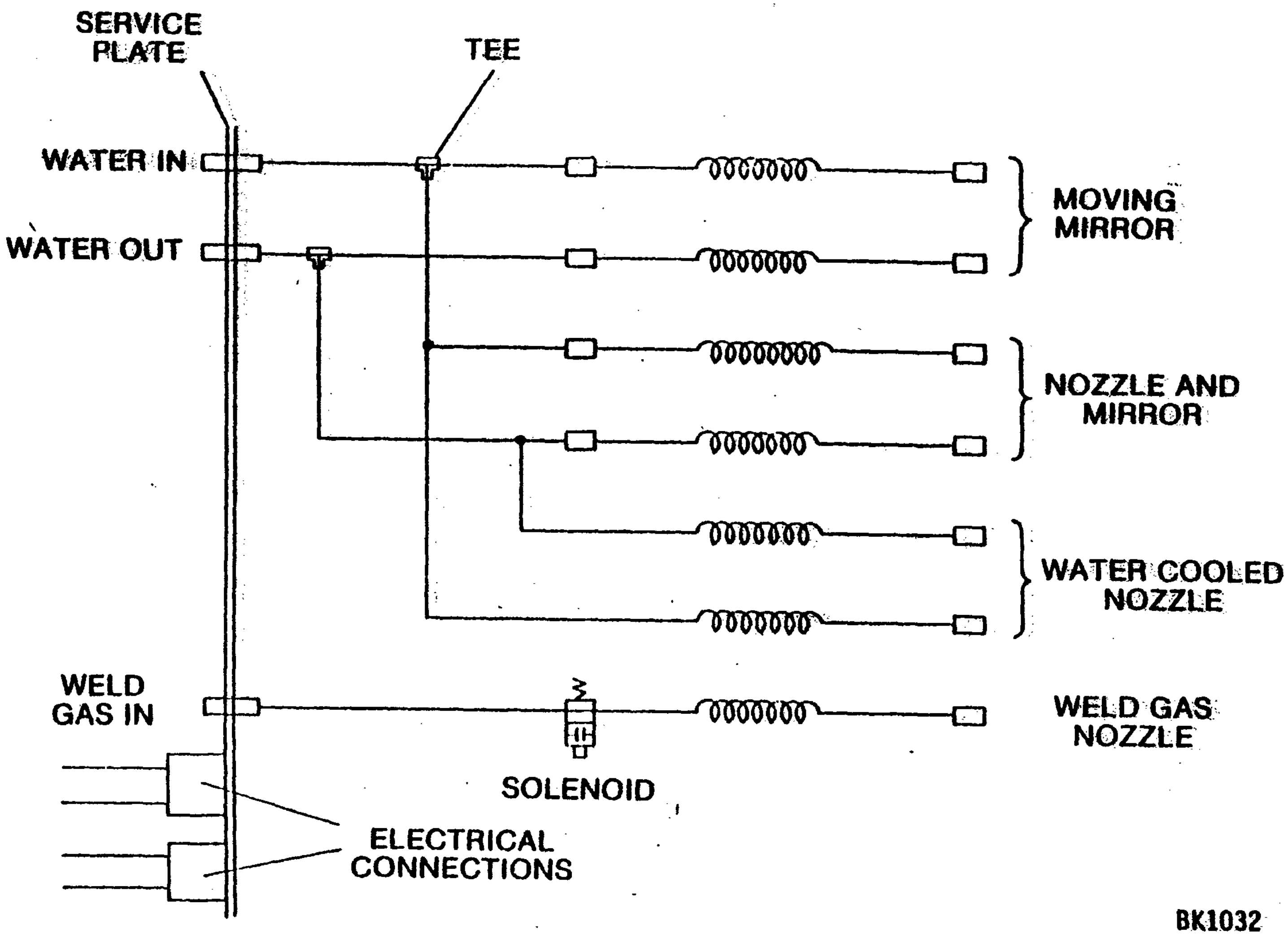



Figure 17
B.O.C. MOVING MIRROR WATER AND GAS SCHEMATIC

### 3.4. Coherent, Inc. Computers.

Three distinct recuperator laser welding systems were built and run at Coherent Incorporated, in this program.

The first laboratory set up used a Coherent owned model 525 laser, an early development set of tools, and an Anorad computer and moving mirror system. It was used to weld various test plates and the plate pairs for two cores; in total about 800 plate pairs.

The second, pilot plant system, originally used a Coherent owned laser, an Anorad computer/moving mirror system, and the first set of production tooling built.

The final production system uses two model 525 lasers identical to those used in the earlier systems, two Allan-Bradley 7100 Controllers and Aerotech mirror tables.

The Anorad computer numerical controller uses a Motorola MC68B00 microprocessor whose program is stored in seven electronic programmable read only memories (E Proms). Each E Prom has a capacity of 2K (2048 words) 8 bit words. In addition, there is a buffer read only memory (ROM) capable of storing 2K words or about 400 instructions. The system uses a 12 volt CMOS BUS and logic to provide improved electrical noise immunity over standard transistor/transistor logic (TTL). The system has a hardware clock, a high-speed hardware multiply/divide, and is programmed in numerical control machine tool language. Input is through a key board and cathrode ray tube which can either display the program seventeen lines at a time or display a position mode. This mode shows the position status (ready, error, home) and offset of each axis at any instant. Because of the processing speed of the system, line by line processing and real time correction of position commands are possible.

To input and develop a new program, the ROM is cleared and then a series of commands are entered which define the shape of the weld path and the external functions (laser on/off, power slopes, shield gas on/off, etc.) which are required at each position. The path steps are defined to the system as either straight lines, by providing the coordinates of the end point, or as segments of a circle by providing the coordinates of the end point, the coordinates of the center of curvature and the length of the radius. The desired length of step on each axis is also entered. The processor then does the linear or circular interpolation needed to generate the machine code for the motion.

Once the program has been developed and debugged, the system will, on command, transfer it to a programmable read only memory which can be removed and reinstated into the machine as desired. This makes job to job changeovers very simple and is an excellent debugging tool, because it allows one to return to a partially successful program which debugging has made worse, in order to try a different approach.

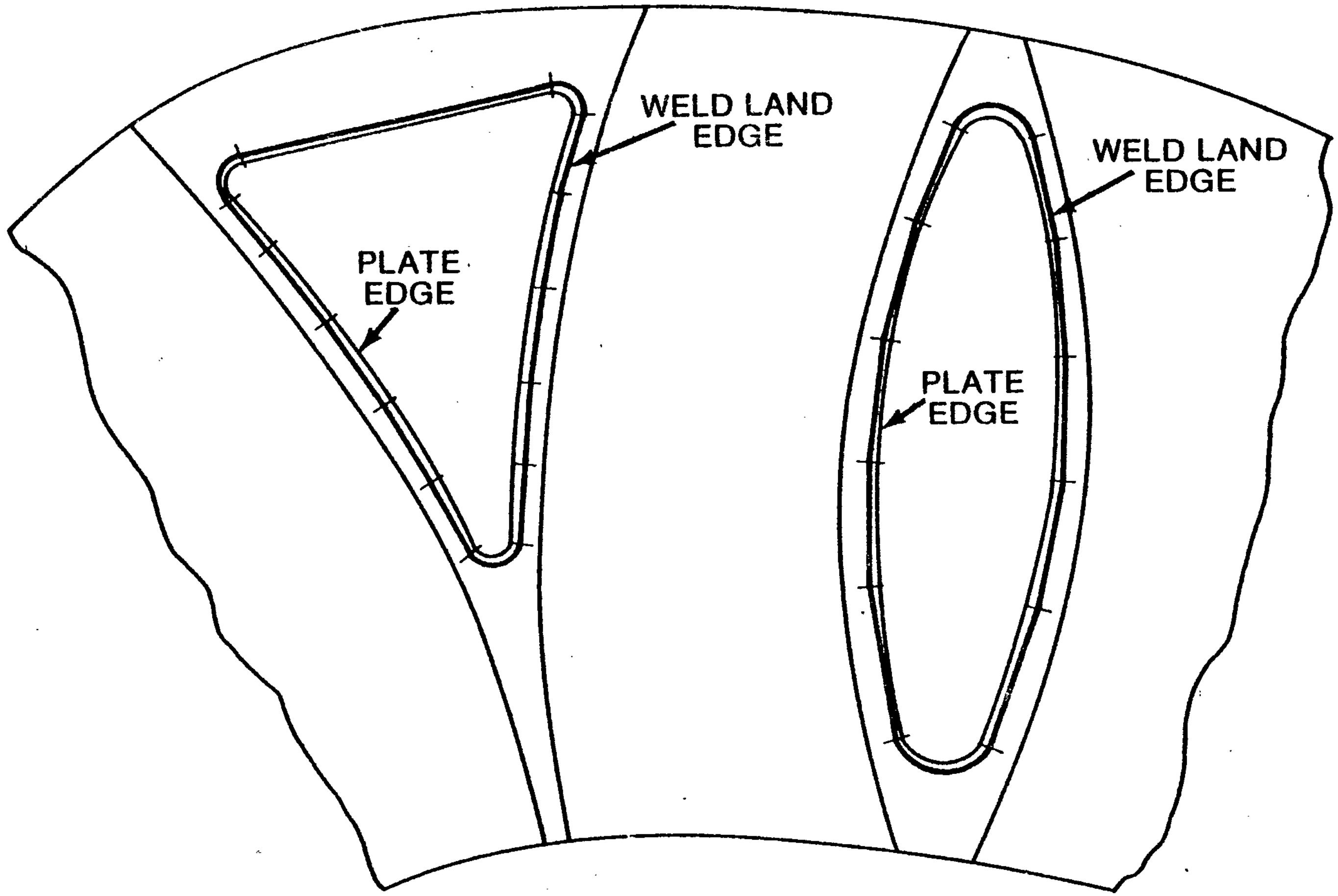
The computer program used to weld the first small lot of plates to test the feasibility of the Coherent welding tools, used a simplified approximation of the joint shape (Figure 18). The arcs at the ends of the ellipse and the corners of the triangle were treated as circular segments. The sides of the ellipse were programmed as a series of straight line segments about 0.75 inch long, as were the sides of the triangle. The outer side of the triangle was programmed as a single straight line. Twenty-five plate pairs were welded with this program, then stacked and resistance welded around the inside and outside diameters into a test pack for pressure testing. It was pressure tight as required, but some laser welding program improvements were found to be needed.

The outer side of the triangle is not supported by corrugations as is the rest of the plate, and is quite flimsy. It was thought that tracking the weld down the center of the 0.3 inch land in this area would increase the rigidity and would make the resistance welding of large stacks easier by allowing less cumulative deflection. This was later found to be unnecessary.

It was decided that, while making this change, the straight segment portions of the program would all be rewritten into segments of circles in order to keep the track centered between the plate edge and the holding die edge (Figure 19). The exposed land for the weld track is only about .04 inch wide in these areas, and the straight segment program caused the laser to alternately approach the part edge and the holding die edge. On a small, essentially homogeneous lot of plates, such as the test pack, this was acceptable. However, to better tolerate the dimensional variations likely to be encountered in a 300 plate lot for a core or in full scale production, circular arc weld tracking was required.

The integrity of the welds produced with this new program was checked by cutting numerous cross sections to assure penetration into the lower plate with sufficient weld width at the interface, and by visually inspecting the plates for evidence of through penetration. When plates so welded around the air holes were joined by resistance welding into a core and pressure tested, numerous tiny leaks were detected.

By peeling the plates along the weld, much like opening a sardine can, it was found that these leaks resulted from tiny .005 - 0.010 inch cross weld holes. At first it was feared that these were somehow inherent to high speed pulsed laser welding. Further investigation, however, showed that each joint had the defects in precisely the same location. The defects on all the elipses were located identically as were all defects in the triangle periphery




BK1022

Figure 18
ORIGINAL WELD PROGRAM TRACK
(COHERENT INC)

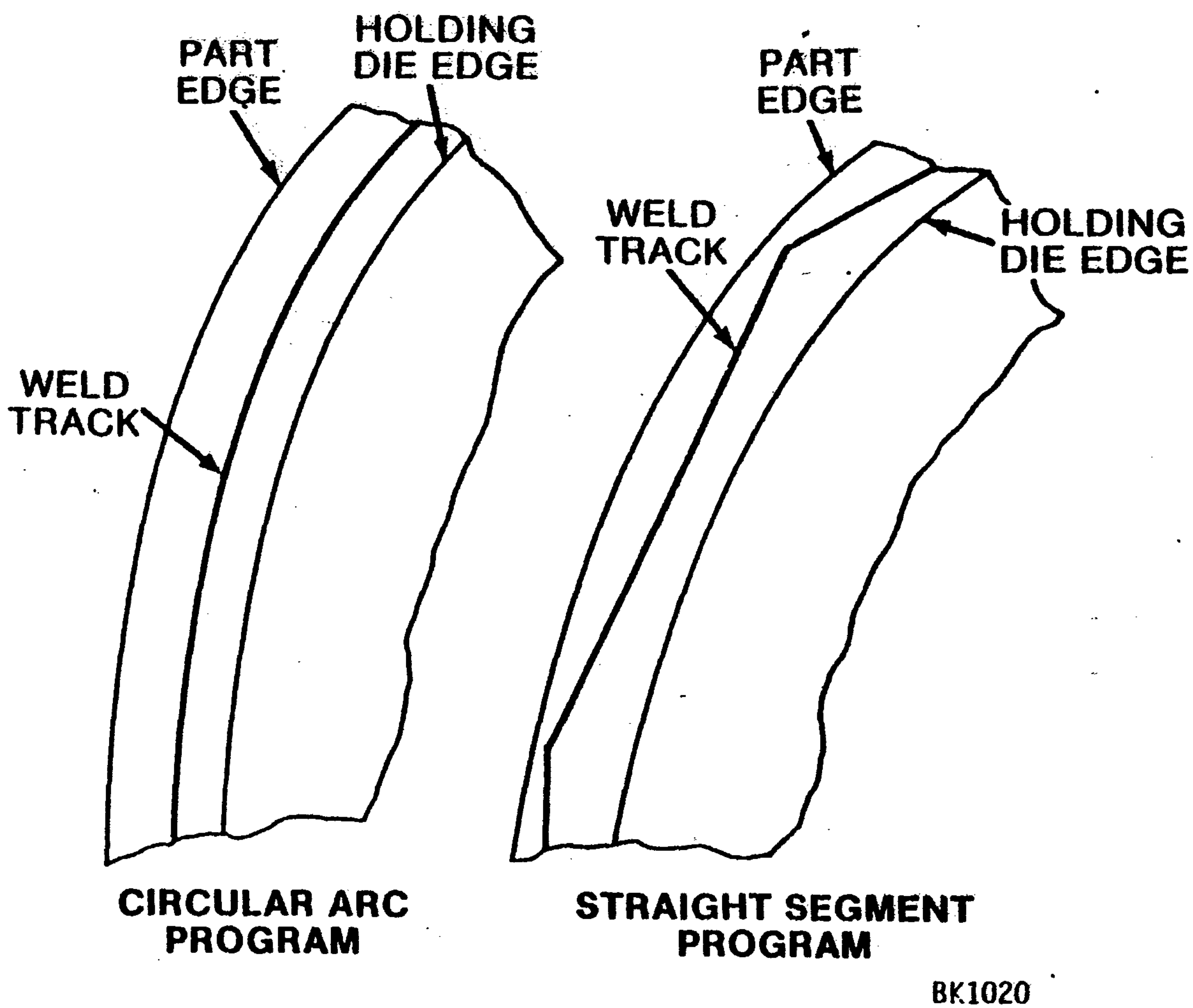



Figure 19
PROGRAMMING OF LARGE RADIUS ARCS

welds. This, of course, indicated that the defects resulted from the computer program.

As explained above, this computer is programmed for a given arc segment by an instruction which gives the coordinates of the segment end point, the coordinates of the center of curvature, and the length of the radius of curvature. But what happens if the arc so defined does not pass through the stated end point? Investigation found that before the next instruction can be executed, the feedback signal from the moving mirrors must indicate they have reached this point. This system, rather than aborting, automatically compensates for this programming error by moving the beam to the specified end point from the closest point on the defined arc. However, this step is not speed controlled because the sharp change in direction requires instant acceleration of one axis and deceleration of the other (Figure 20). The loss of penetration caused by these high-speed jumps caused the pin hole leaks.

A third program was then written and verified, first by low power pulsed runs on paper, then by welding and destructively testing plate pairs. In low power tests on paper, the laser is turned down to about 50 Watts and the program run with regular bond paper in the holding tools. Depending on the pulse repetition rate selected, either a fine cut-out of the weld track shape or a series of tiny holes in the paper tracing the track is obtained. Visual inspection of these paper tracks at thirty magnifications was used to find any jumps. The program was then modified to eliminate them.

Once a smooth, jump-free track was developed on these paper cuts, plate pairs were welded together and destructively tested. Rather than just cutting random cross sections, about thirty feet of weld was peeled longitudinally along the heat affect zone at the edge of the weld and inspected under a microscope at thirty magnifications for cross weld pin holes. None were found. This technique is now standard for certification of new programs and weld perameter sets.

Once the new program had been verified, twenty-two new plate pairs were joined with it, then fabricated into a pressure test pack. This pack had no leakage when tested at the production recuperator test pressure.

Next, three hundred plate pairs were joined by the new program and fabricated into a complete recuperator core. It, too, had no leakage when tested to the production requirements. This core was one of those used to engine qualify the laser welded recuperator. (see Chapter V).

The production system is controlled by two Allen-Bradley 7100 units. These C.N.C. language programmed computers use 16 bit words with a seventeenth parity bit added by the controller. These computerized controllers are designed to control the operations of a

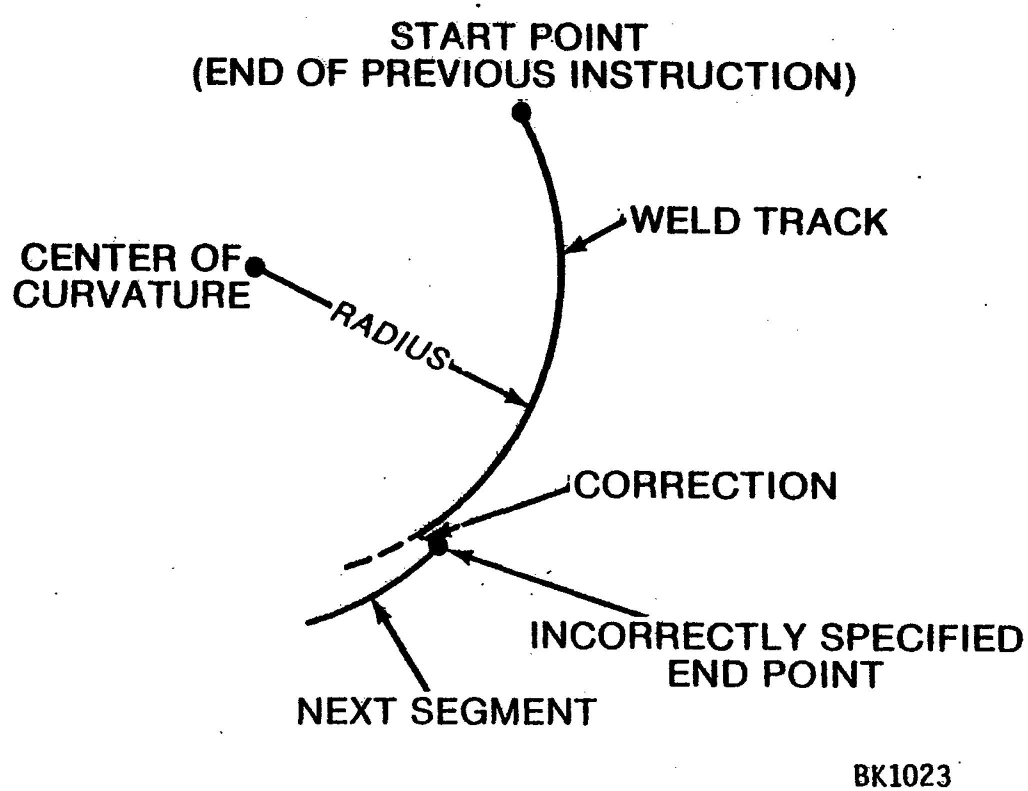



Figure 20
CIRCULAR SEGMENT PROGRAMMING ERROR

number of machine tools using essentially the same firm ware. They can control up to four axis.

The controllers are equipped with programmable interfaces which allow the separate programming of input/output interface logic. This significantly reduces the central processor interrupt work load.

Input/output to the controllers is either through magnetic tape or by the front panel keyboard and CRT in the edit mode. Figures 21 - 23 are the flow charts of the programs for the production facility.

In addition a program was also developed for the rework of plates with indication or lack of weld in one or more hole pairs. This program allows rework of either laser or resistance welded plates.

## 3.5. Coherent Moving Mirror Systems.

All moving mirror systems used the same general layout as B.O.C.'s with the columnated laser beam reflected by two moving mirrors set at $45^{o}$ to the beam path.

Laser output is through a 5 inch gallium arsenide lens mounted as shown in Figure 24. There is one inch of adjustment of focal point location provided by a standard micrometer. The output lens is protected by a stream of inert gas (helium) injected into the laser path downstream of the lens.

The moving tables to which the mirrors are attached ride on roller bearings enclosed in diamond shaped channels formed by V-slots in the table and rails. The tables are driven through drive screws by direct current motor/tachometers. Position signals are generated by rotary encoders monitoring the motor shaft position.

The superiority of gallium arsenide output lenses over those made of potassium chloride must be mentioned. This is the result of gallium arsenide not being hydroscopic and of its greater thermal conductivity; 0.45 Joules/second/cm/$c^{o}$ compared to 0.065 for potassium chloride. Potassium chloride does have superior theoretical transmission characteristics for $CO_2$ laser radiation. The difficulties of obtaining and maintaining lens quality polished surfaces on a strongly hydroscopic material, however, cause actual lenses of potassium chloride to have much higher absorptions than the theoretical value. This and their poor conductivity results in very short service life because of a phenomenon called thermal runaway. The laser energy absorbed by a lens is converted into heat which must be dissipated. The ability to dissipate heat is a function of the rate of absorption and the thermal conductivity. The rate of absorption generally increases with temperature. If heat is not dissipated fast enough, thermal runaway results in the lens suddenly and for no apparent reason, breaking. This happened several times while running the B.O.C. with a potassium chloride output lens. It never occurred while running a Coherent system with gallium arsenide lenses.

PROGRAM "MAIN"

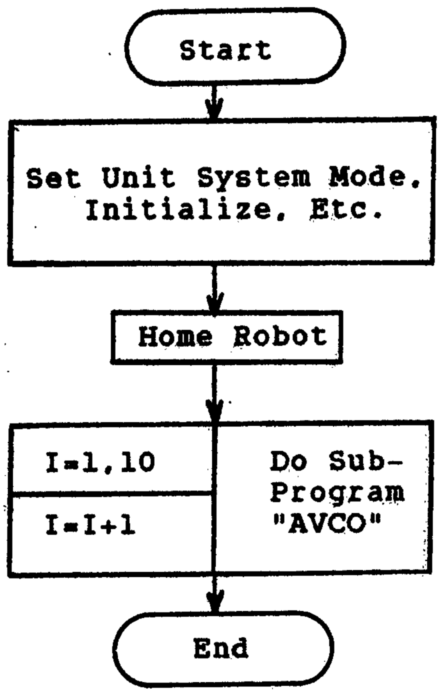



Figure 21 FLOW CHART OF PROGRAM "MAIN"

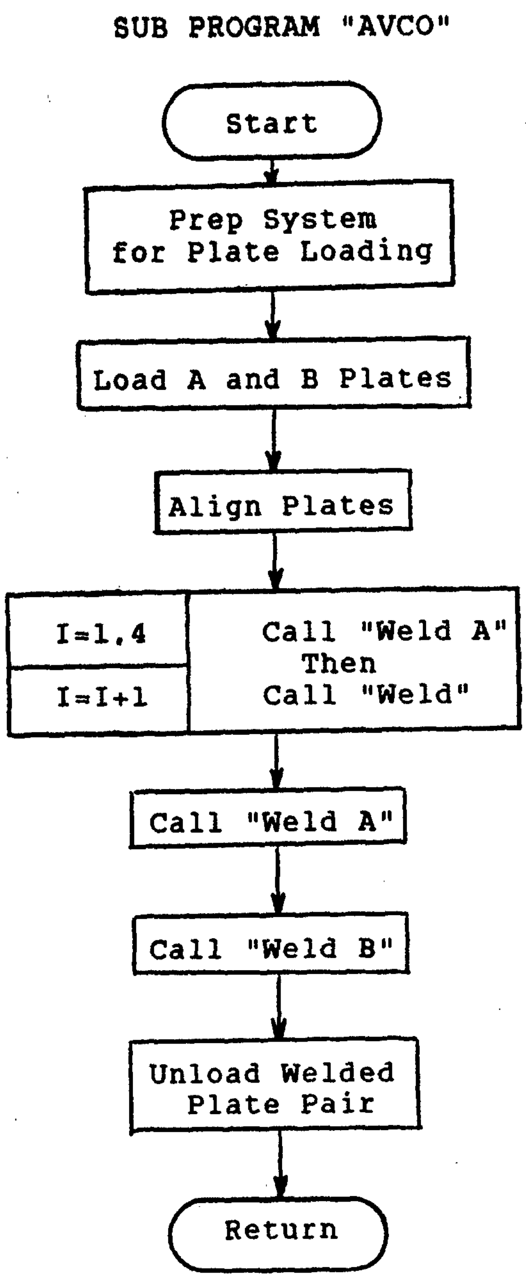



Figure 22 FLOWCHART OF SUBPROGRAM "AVCO"

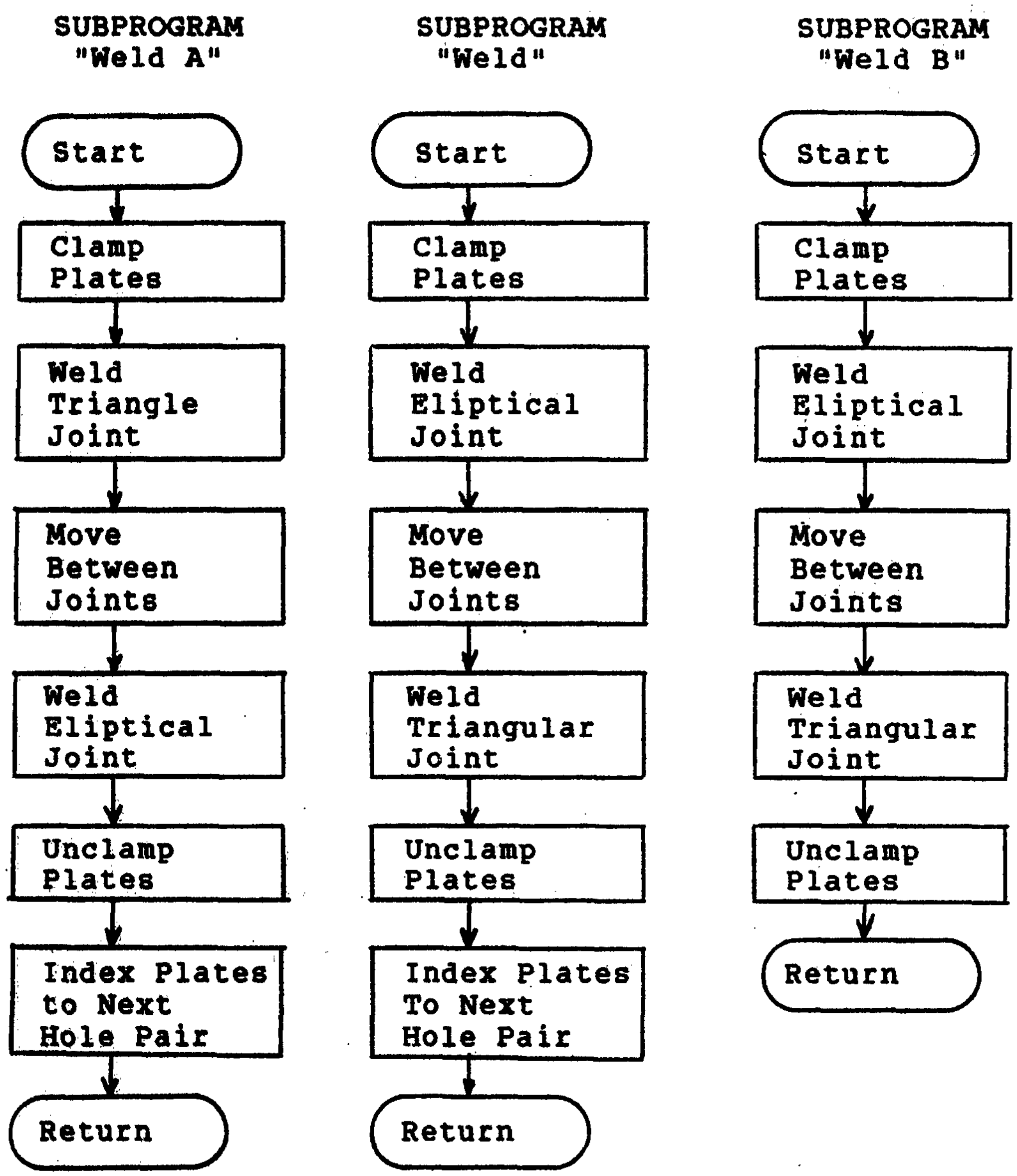
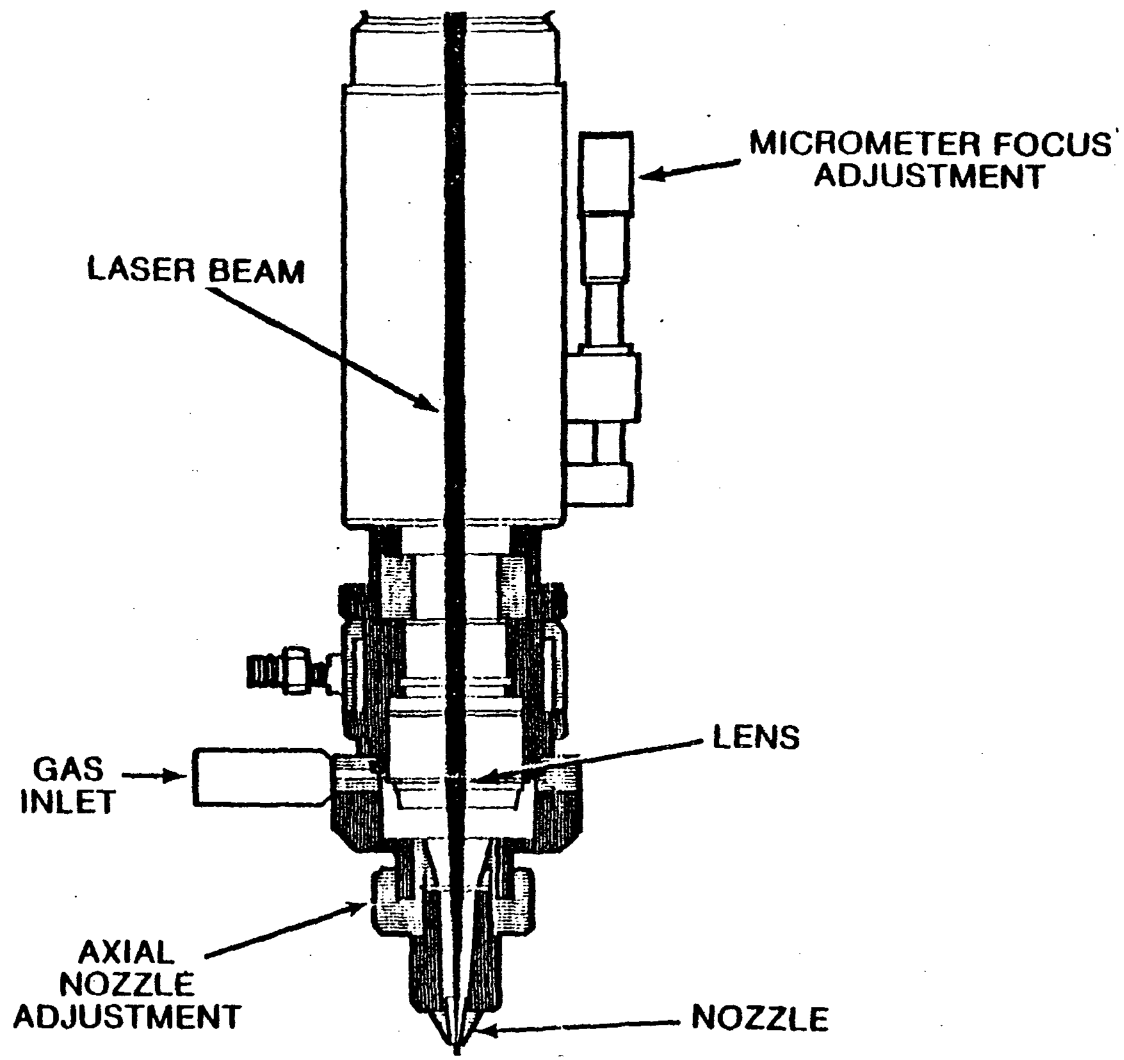



Figure 23 FLOW CHARTS OF WELDING SUBPROGRAMS




BK1030

Figure 24
COHERENT INC BEAM OUTPUT LENS AND NOZZLE

## List of References

Strait, B. Thuot, M. and Hong,J. 1977. A Distributed Microcomputer System for a High-Energy Gas-Laser Facility. Computer, 10:9:36-43.

## 4.0. ANALYSIS AND COMPARISON OF TOOLING

### 4.1. Introduction.

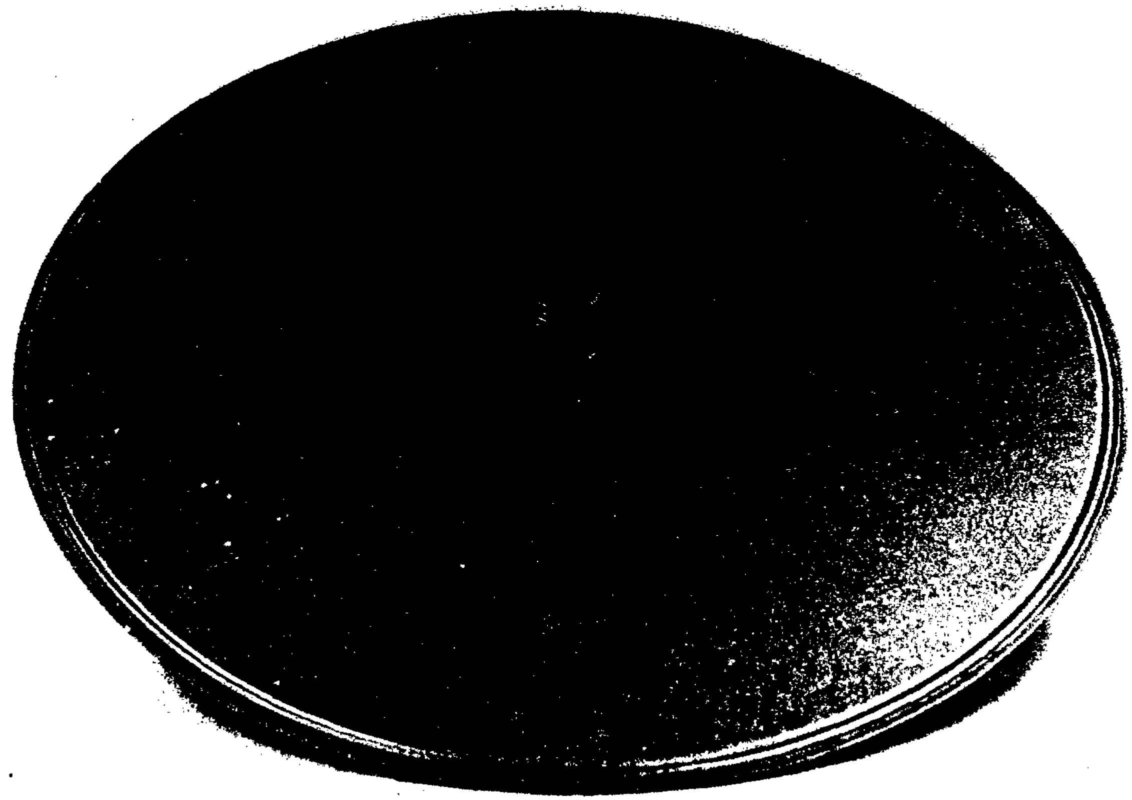
The tooling is defined as that part of the system, below the output nozzle of the moving mirrors,which holds and manipulates the pairs of recuperator plates for welding. It can be divided into the holding tools which clamp the joints tightly together during welding, the index table which rotates the plates between welding of hole pairs, and the load/unload device.

The basic indexing concept was defined early in the program. One triangular hole joint and one eliptical hole joint would be welded as a unit by the moving mirrors, and the plates would be indexed between weld cycles. Ten weld/index operations are required to join one A-plate to one B-plate. This approach was selected because it allows the tooling and plates to be stationary during welding and avoids the problems of mechanical inertia involved in moving these large masses to track the joint shapes.

Moving mirror systems which can deflect laser beams over areas of up to about 6 feet x 12 feet are commercially available. They are, however, designed for textile cutting and operations where uniform velocity around small radii is not as critical as it is in welding. Systems with the required accuracy of velocity control are only available with travel up to about 12 inches x 12 inches. Hence, the decision to clamp and weld one pair of holes as a unit, and index between hole pairs.

### 4.2. Holding Tool Concepts.

In order to make sound welds between 0.008 inch thick steel, it is absolutely essential that metal to metal contact be maintained. The least cumbersome method for maintaining contact at the weld joints would be to partially evacuate the passages between the plates during welding. In order to test the feasibility of this approach, a prototype set-up was built. This consisted of a vacuum pump and tank to act as a vacuum reservoir and seals and ducting as required. The concept was first tried with a simplified circular specimen simulating the recuperator joint (Figure 25). (These specimens were originally designed for basic welding parameter development and for low cycle fatigue tests by cyclically pressurizing at $1300^{o}$ fahrenheit, simulating the service conditions for a recuperator (see Chapter V). The vacuum concept worked satisfactorily on recuperator test specimens because their simple symmetrical shape and center access fitting made pump connection simple. When applied to full size recuperator plates, the problem of vacuum connection is much more difficult because air must be evacuated from the plates at the edges. Removal of air at a sufficient rate to maintain the necessary pressure differential at the joint lands was not possible. Therefore mechanical fixtures must be used to hold the plates together during welding..



MAG 1X

Figure 25

RECUPERATOR LOW CYCLE FATIGUE TEST SPECIMEN

There were two alternatives for the basic design of the mechanical clamping tools: the tooling could maintain contact between the plates by bearing on the outer edge of the joint area or on the inner side.

Early in the development of laser welding techniques for recuperator plates, experimental tooling for the two concepts, hole side and part side (Figures 26 and 27) were made both for recuperator plate segments and for the low cycle fatigue test specimens.

Each tooling concept has advantages. Hole side tooling provides much more positive clamping of the joints since it holds the plates so they cannot separate during welding due to thermal stresses. It has two disadvantages: sensitivity to burrs from the plate punching operations, and the difficulties of automating tools designed with this concept. Finding ways to over come these two disadvantages was a major part of the tooling development effort in this program.

The punch dies for recuperator plates are large and very complex. Figures 28 and 29 show the full plates. The inco 625 plate material is 0.008 inch thick and very ductile (35 percent elongation). This requires dies with very close clearances to produce clean, burr-free cuts. The size of the dies coupled with variations in operating temperatures makes these clearances impossible to maintain in practice. If the plates are punched so the burrs face inward, between the plates, they interfere with joint closure. If the plates are punched so the burrs face outward, a high wear rate on the welding fixture clamping die could result.

In Phase II of this program, B.O.C built a prototype full plate fixture using the hole side concept (Figure 30) The figure clearly shows the difficulties in designing such a fixture to automatically open and close for rapid loading and unloading in a high volume production operation. It also shows the difficulties of having a full plate holding tool and indexing it, due to dimensional problems associated with accumulation of tolerances between the plates and the tools.

Part side tooling is insensitive to burrs, if the parts are punched so the burrs face up on the top plate and down on the lower plate. However, it does not provide the positive clamping of hole side tooling and will not compensate for rounded joint flats caused by worn forming tools. It can be very readily automated. In Phase II, Coherent built and evaluated tooling using this concept (Figure 31) on the original laboratory system.

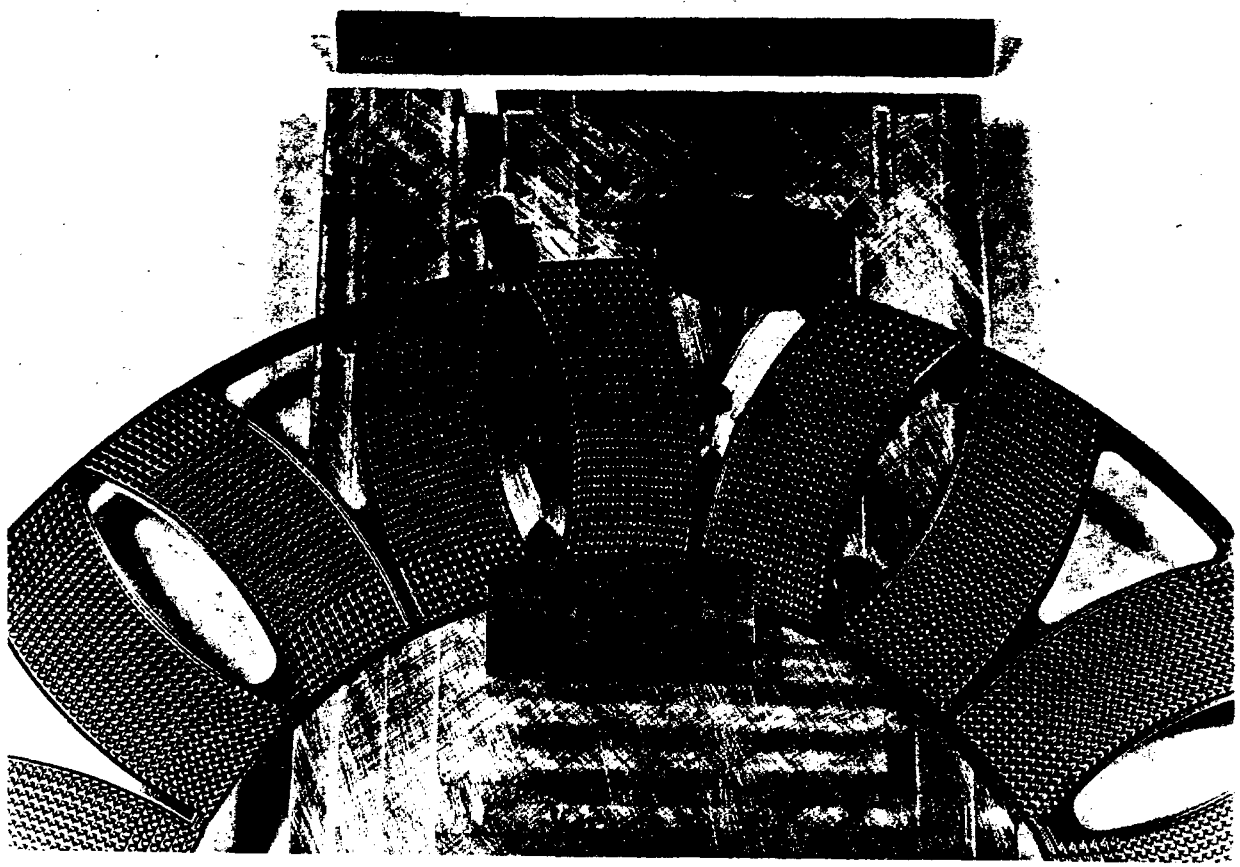


Figure 26

PHASE I HOLE SIDE RECUPERATOR SEGMENT FIXTURE

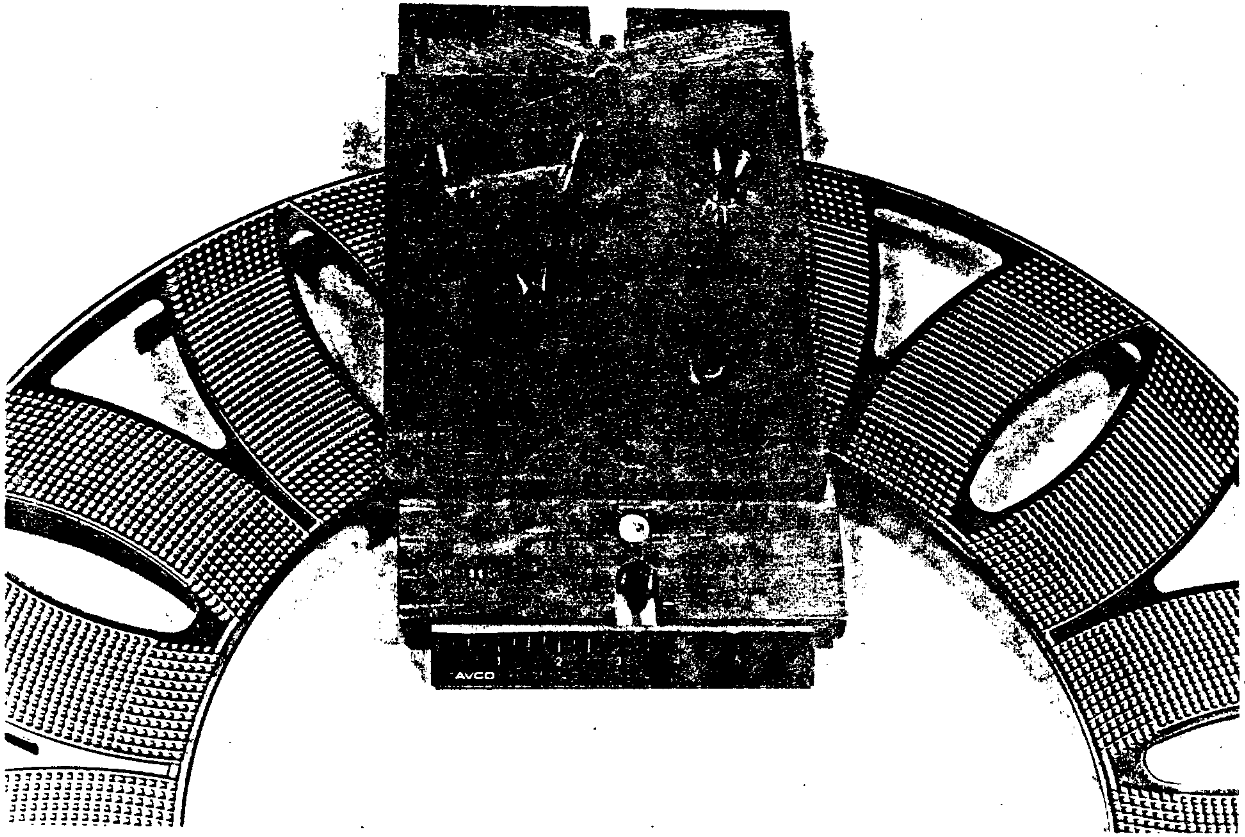



Figure 27

PHASE I PART SIDE RECUPERATOR SEGMENT FIXTURE

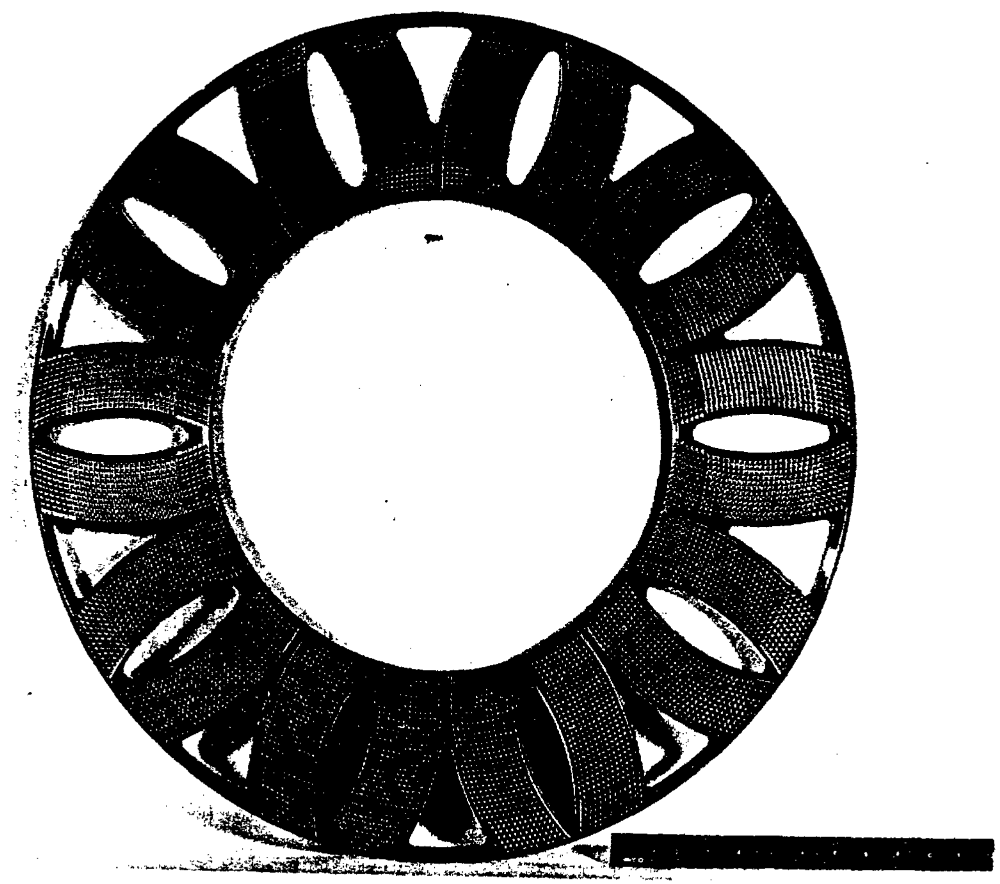


Figure 28
RECUPERATOR PLATE "A"

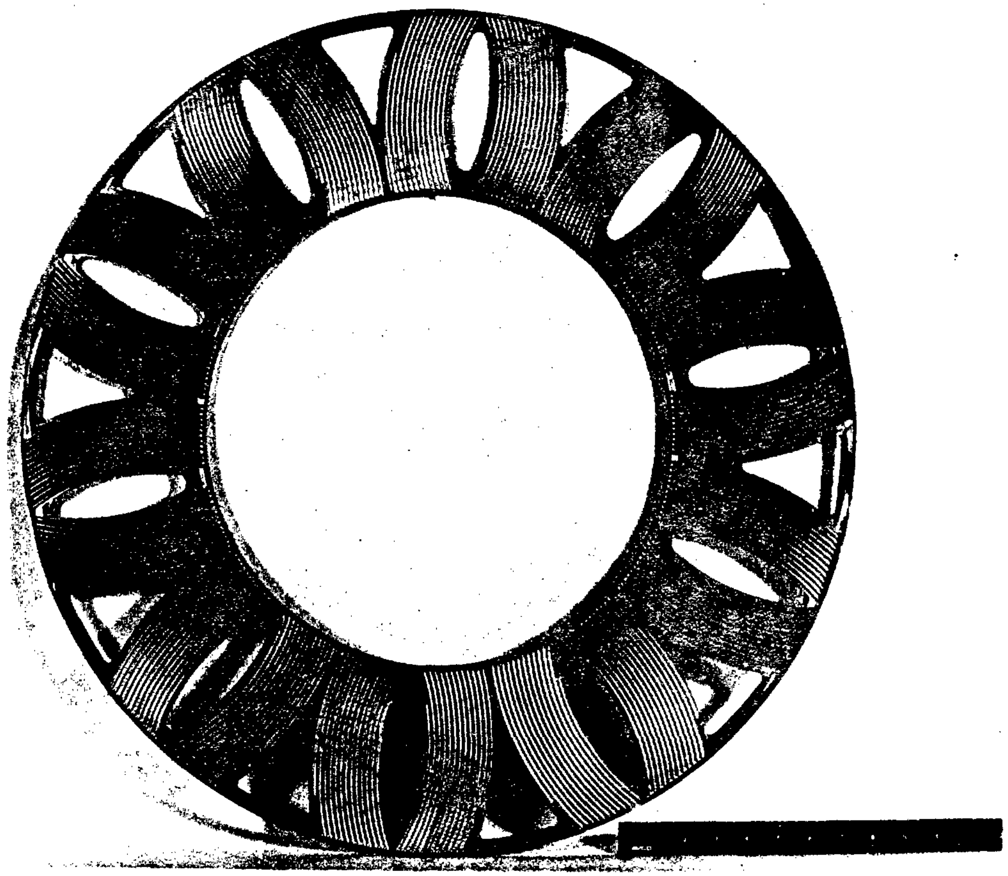


Figure 29
RECUPERATOR PLATE "B"

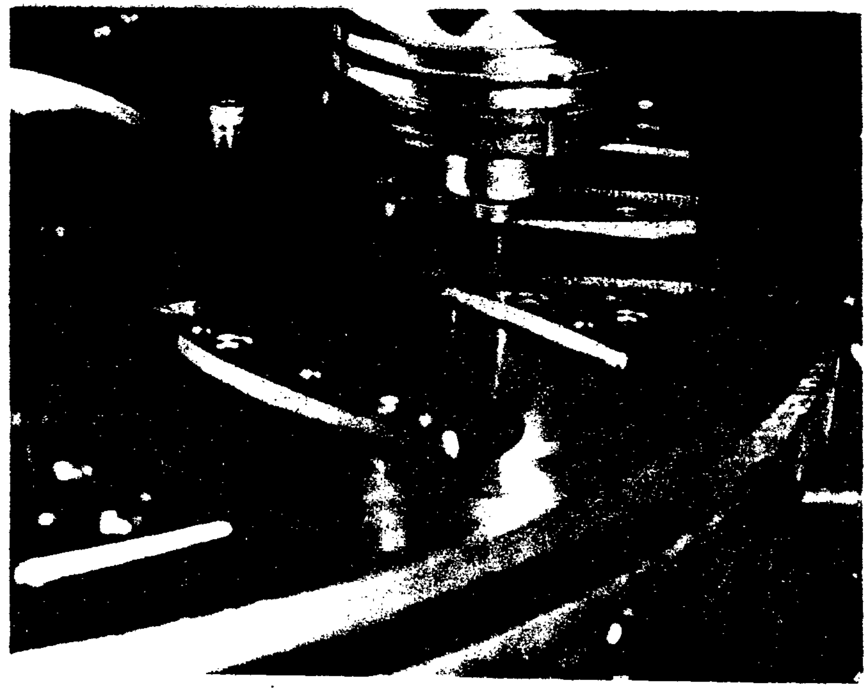


Figure 30

PHASE II HOLE SIDE TOOLING

The welding holding tools must compensate for deficiencies in the forming and punching dies which make the recuperator plates. In addition to the problems with burrs and joint land flatness, the problem of overall tolerance accumulation around the plates must be addressed. There are ten pairs of holes spaced around the annular plate. The plates are made in a large multi-stage press which forms and punches the plates as material is fed through it. These operations are performed by four sets of tools, each of which does one operation on the entire plate.

The dies are made up of individual segments mounted in a die frame. It is not possible to build such a large device so that all segments are in precisely the same relationship to all other segments. Therefore, if the entire plate is to be fixtured for welding, as a unit, some technique for assuring circumferential registration between the forming and punching dies, and the welding tools is required. This is far too cumbersome for use in a high volume production line unless no better alternative is available. The answer to this problem was to use one set of welding tools permanently mounted under the moving mirrors and to move only the plate pair between welds.

4.3. B.O.C. Tooling Development.

During this early portion of the program, no automated indexing systems were built; but manually operated systems for evaluation of concepts were built and tested. The first concept was the prototypes of the full surface plate tool built by B.O.C. This tool was mounted on a turntable which was manually rotated between hole pair welds and positioned for each weld by an index pin inserted into a locating hole. This concept worked in combination with hole side tooling because hole side tooling with its very positive plate contact across the entire land (burrs permitting) allows some variation in laser track location on the land. Variation will, of course, occur because of the tolerance bands of clamping tool and index table dimensions.

At the end of Phase I, this tooling approach, hole side full plate holding tools indexed from weld to weld, was considered to be the most promising. However, as experience was gained in Phase II, it was learned that, although the concept worked when welding individual pairs of holes in the Phase I prototype tool (Figure 26), the problems of building a full plate tool this way and assuring its dimensional compatibility with the plate manufacturing tools were insurmountable. The punching and forming dies are constantly, subtly changed by wear, sharpening and other maintenance. These tooling problems were a major factor in the B.O.C.'s decision to withdraw from the program.

## 4.4. Coherent Inc. Prototype Tooling Development.

Figure 31 is the part side tool developed by Coherant early in Phase II. In the stationary tool frame are a set of dies which fit around each hole and tightly squeeze the joint lands together. The top die is fixed and the lower one is driven from a down/open position to an up/closed position by an air diaphragm. This tool overcomes the problem of tolerance accumulation and registration with the forming and punching dies very simply; it treats each pair of hole joints as a separate unit. The holes to be welded are positioned by two pins bearing against the inside of the plate annulus adjacent to that hole pair and a third pin located at the inner end of the adjacent elliptical hole. Therefore, accumulation of tolerances does not occur as indexing and welding progresses around the plate pair.

Part side tooling requires very precise location of the laser track in relation to the part clamping dies, because it does not assure tight fit across the entire land as does hole side tooling. The only way to meet this requirement of close laser track to tool position is to lock the part holding tools in one location and move only the recuperator plate pair. The clamping dies are opened and one pair of hole joints are inserted. The dies are closed, and the welds are made. Then the dies open and the recuperator plates are rotated so the next pair of holes is in position within the dies. The dies then close and the next weld is made. In this way, the very precise relationship required between the clamping dies and the moving mirror system computer program is maintained.

These tools were used to weld about 800 plate pairs during Phase II. They proved to be rugged and dependable and no reason was found to expect problems in building an automated facility based upon them. However, their tendency to accumulate weld spatter and their sensitivity to plate pair dimensional variation in the convolutions to hole edge dimension lead to further work. During the design of the production facility this work yielded the tool design used on this production facility.

This final tooling design (Figure 32) again uses the hole side gripping concept. The tool in mounted on a die set which rises and inserts the gripping tools through the part holes. The tools then expand as they are pulled downward by the die set thus gripping the edges of the recuperator plates and pulling them together.

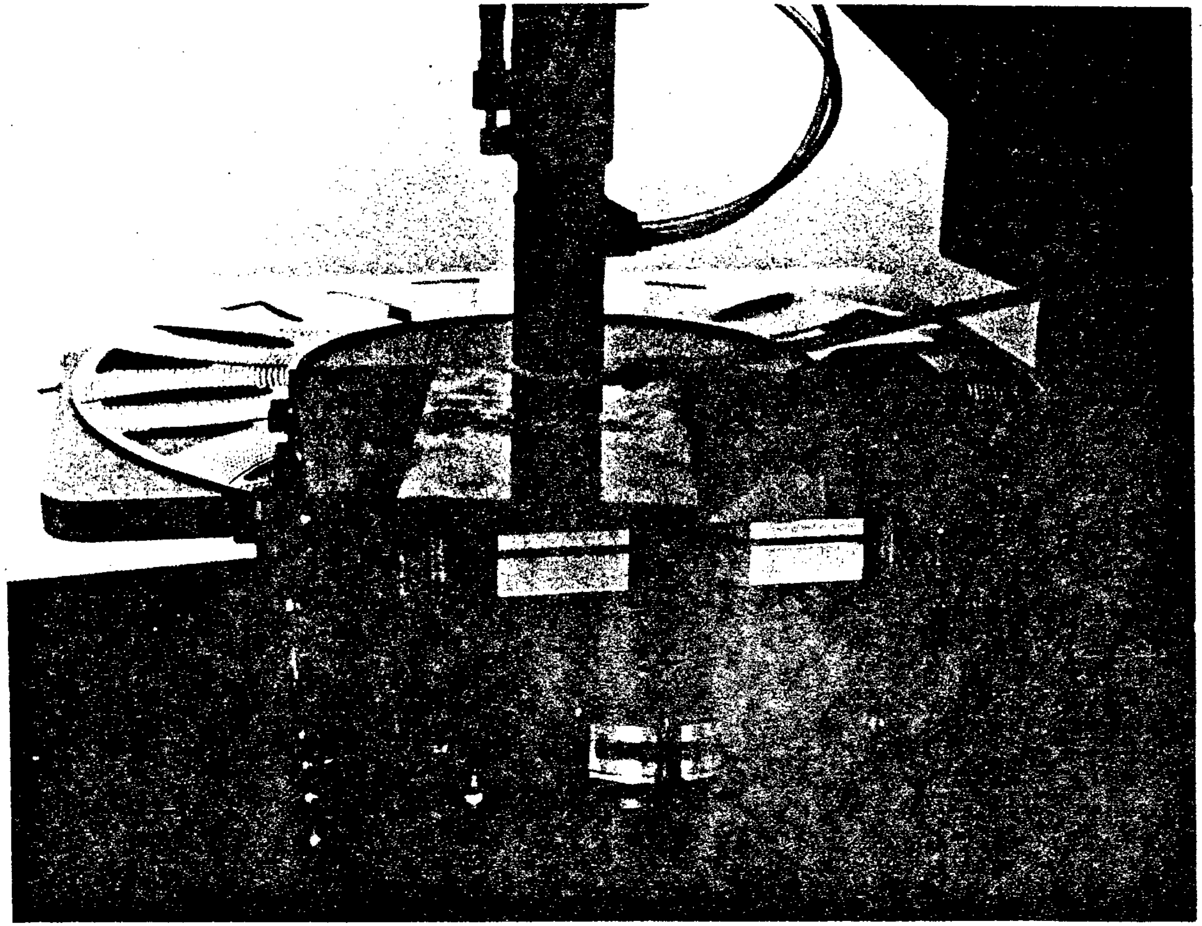


Figure 31

PHASE II PART SIDE TOOLING

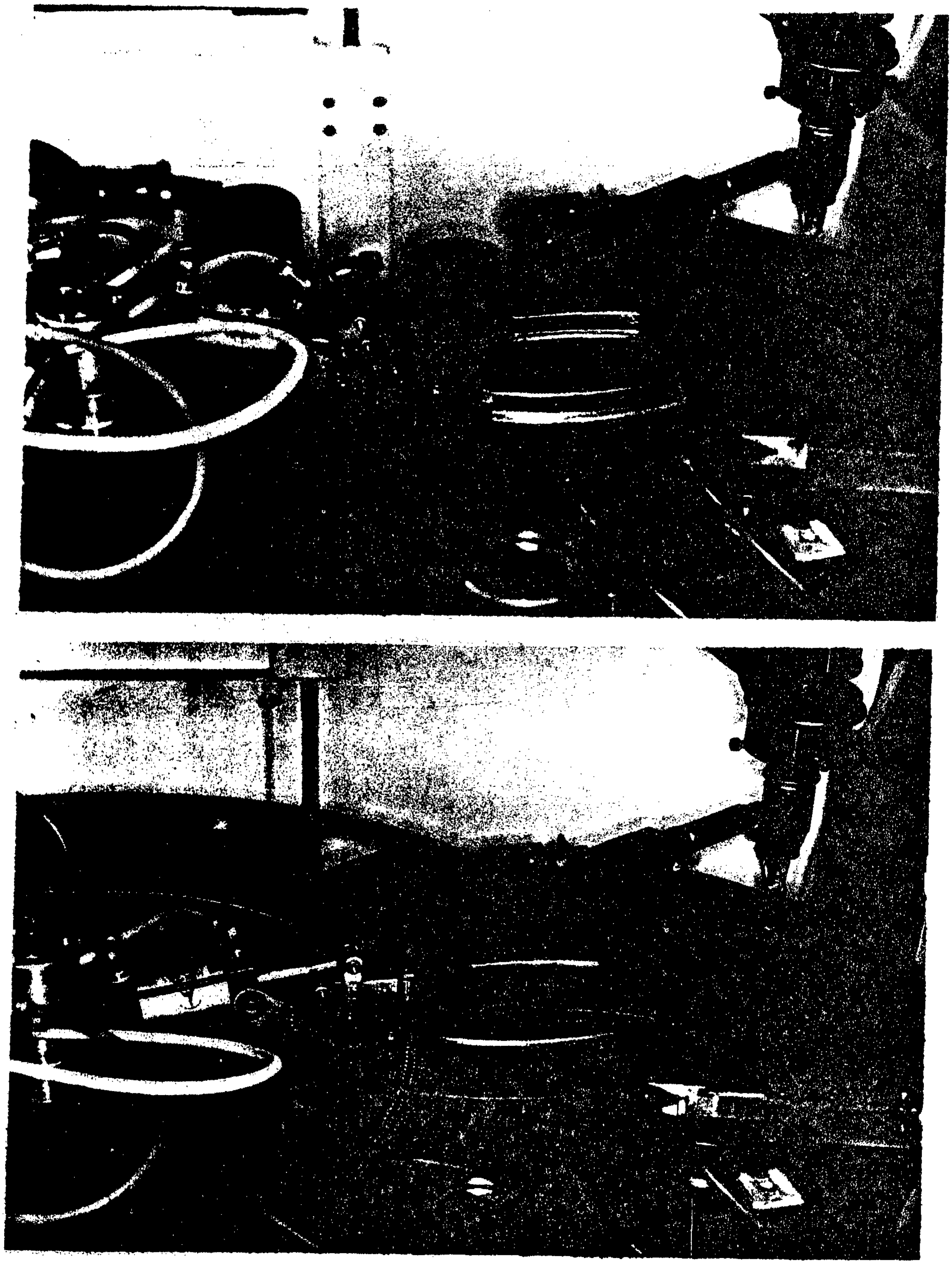


Figure 32
PHASE II PRODUCTION WELDING TOOLING

## 5.0. EVALUATION OF LASER WELDS AND LASER WELDED RECUPERATORS

### 5.1. Introduction.

During the course of this program literally thousands of feet of laser welds were evaluated. These evaluations were by four methods: destructive analytical techniques, fatigue tests, engine tests, and non-destructive tests. Welds from several subcontractors made with many parameter combinations were evaluated but, of course, the system and parameter set finally developed for production were subjected to the most exhaustive evaluation. Figure 33 shows the typical cross sections, top and underside of the welds made by the production system.

### 5.2. Testing of Welded Internal Pressure Fatigue Specimens.

Comparison of laser and resistance welding was conducted using low cycle fatigue testing of internal pressure specimens. These test specimens, as shown in Figure 25 were made of 0.008 inch thick Inconel 625 sheet material and represent the range of weld parameters and techniques developed in the various phases of this program. Testing was performed at 1300°F (704°) by pressurizing the specimen with nitrogen gas at 360 cycles per hour until failure of runout. Test results are plotted in Figure 34. Within the range of pressures tested, the laser and resistance welded specimens were comparable in fatigue strengths as determined by the following standard S-N curve fitting method.

$$P_i = \frac{P_t}{1 + \frac{B}{(N/10^3)^{\gamma}}}$$

where $P_i$ = the pressure at which infinite specimen life can be expected (fatigue strength)

$P_t$ = test pressure

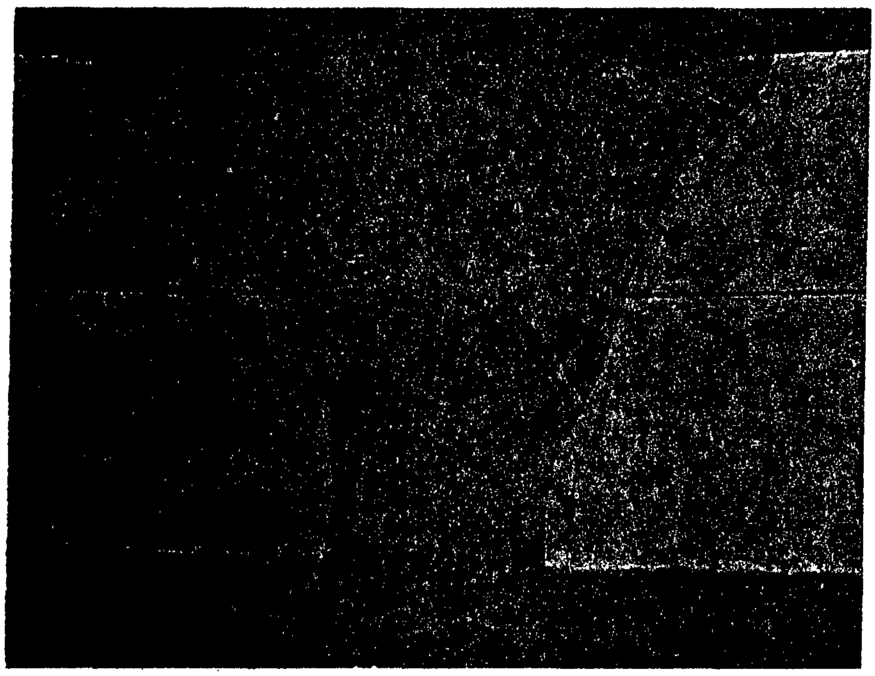
$N$ = number of cycles to failure or runout

$B$ = curve fit parameter = 2.0

$\gamma$ = curve fit parameter = 0.5

Note: and B are selected to minimize standard deviations from individual points fitted to the mean S=N curve

The calculated mean internal pressure fatigue strength was 231 psig for the laser welded specimens and 215 psig for the resistance welded specimens. The wide scatter of data within each of the two populations was due to the range of weld parameters used. The vast majority of failures in both types of specimens occurred at the weld fusion line location, with the remaining failures at the weld centerline. It can be concluded from this fatigue evaluation that comparable performance can be expected from laser and resistance welded parts.



**Etchant: Marbles** MAG 150X

Figure 33

PRODUCTION LASER WELDS

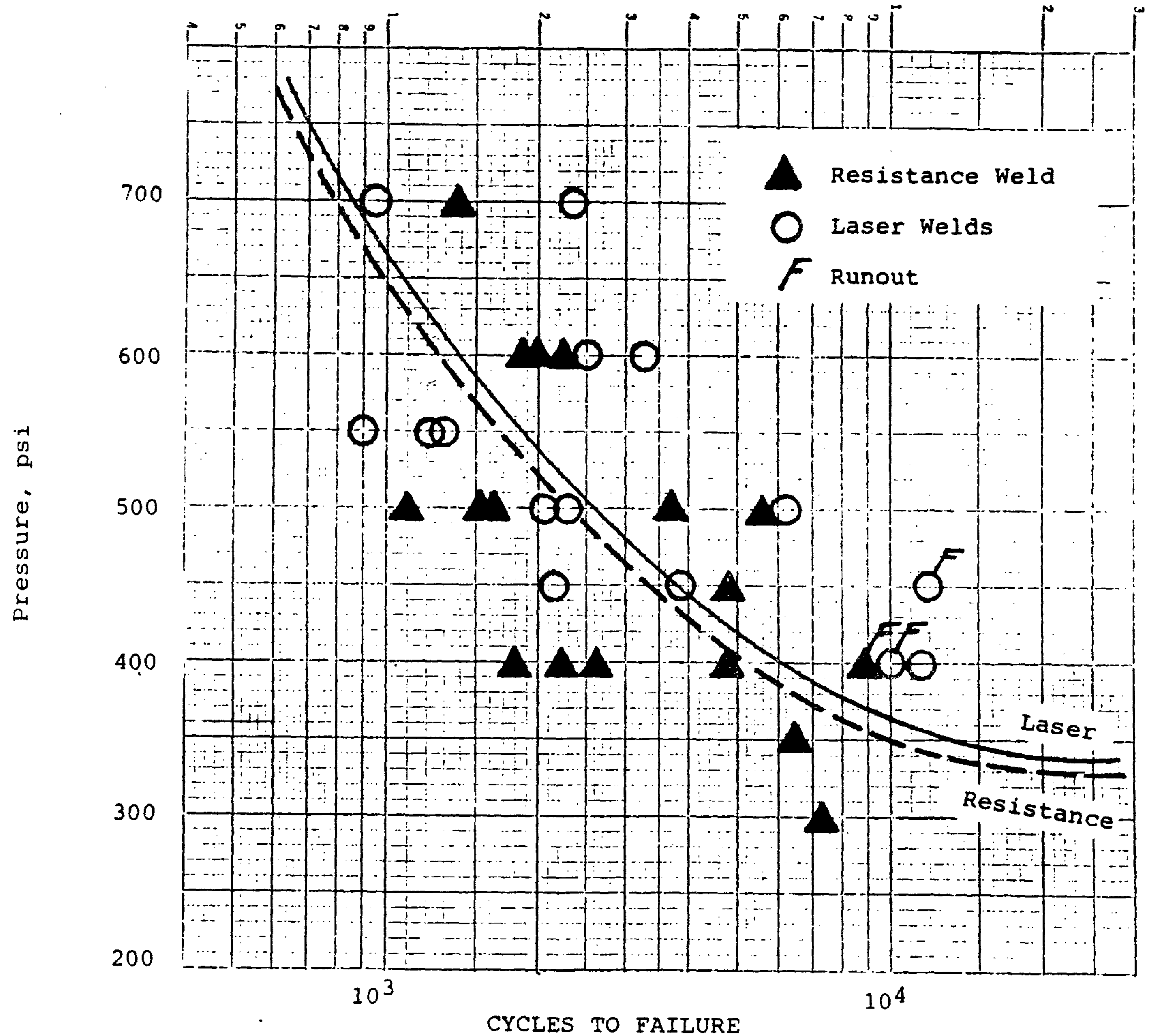



FIGURE 34. LOW CYCLE FATIGUE RESULTS PLOTTED

### 5.3. Engine Qualification Tests of Laser Welded Recuperators.

Two recuperator cores made of laser welded plate pairs were engine tested for qualification.

The first was run for 459 hours on Engines A54 and A31 at Detroit Desel Allison Division on cyclic transmission testing. It was then returned to Lycoming where the recuperator module was disassembled and the laser welded core tested to new part standards. No deterioration of the core was detected.

The second core was run on Engine LE 85008 at Lycoming. During this test it ran a total of 488 hours of which 420 hours was mission profile testing. It too, was found to have suffered no deterioration from new part standards during the test.

### 5.4. Laser Weld Anomalies and Acceptance Limits.

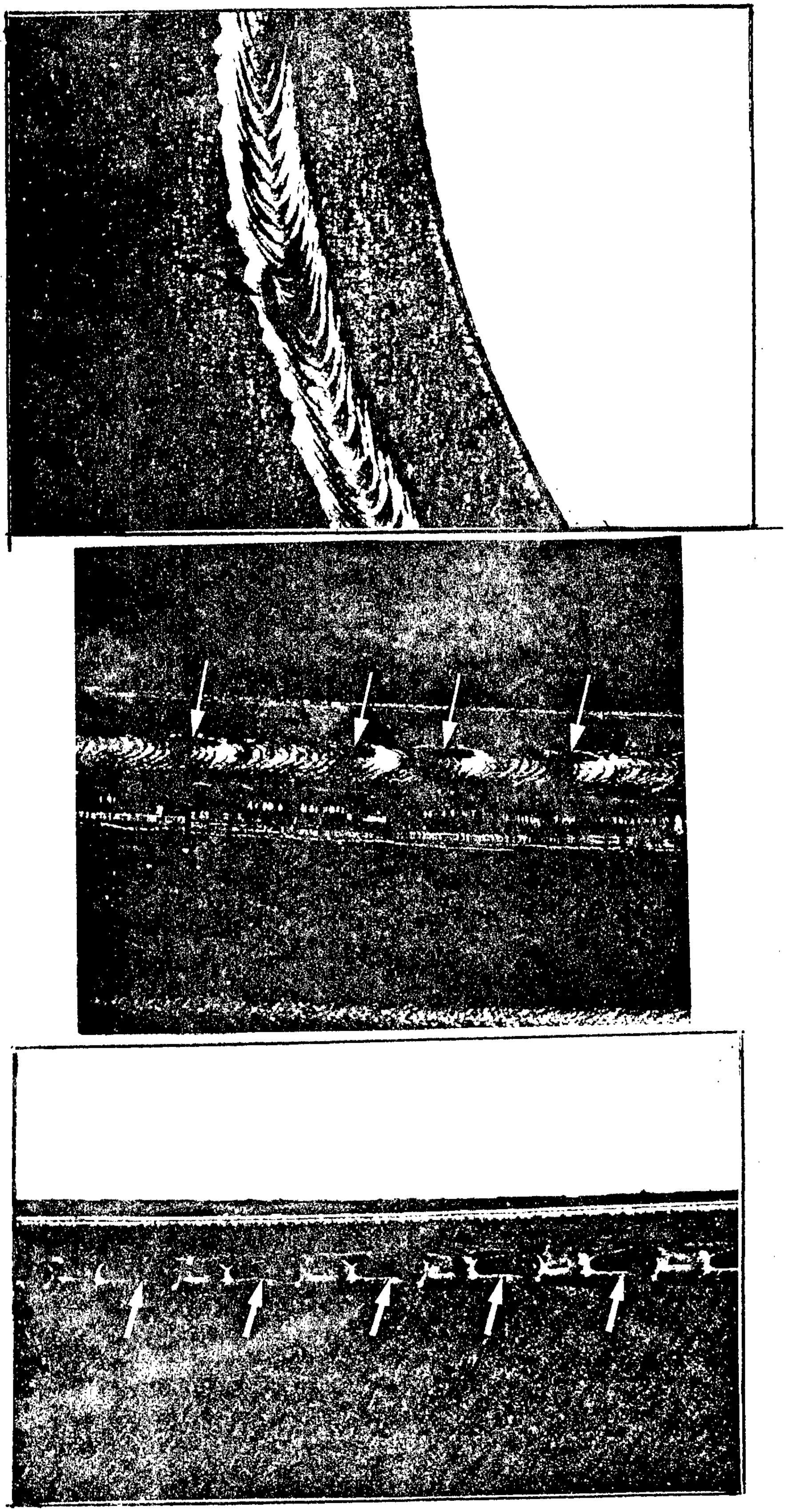
During the laser welding procedure development, surface anamalies were encountered in the visual inspection of some of the welds. In order to set reasonable production qualitiy limits, these anomalies were evaluated.

5.4.1. Undercutting. Figure 35 shows typical weld undercutting. This anomaly is the melting away of the base metal, usually caused by inadequate contact between the two plates to be joined. It was located either at the weld edge or center, usually chain-like and through the top plate thickness, and is generally readily detectable visually. Some of the undercut areas had no weld or fusion at the joint interface.

5.4.2. Melt-through. Representative melt-through holes are shown in Figure 36. They are attributable to reduced thermal mass or increased energy input produced by uncontrolled changes in welding conditions. They generally had a diameter approximating the weld width and were easily detectable visually.

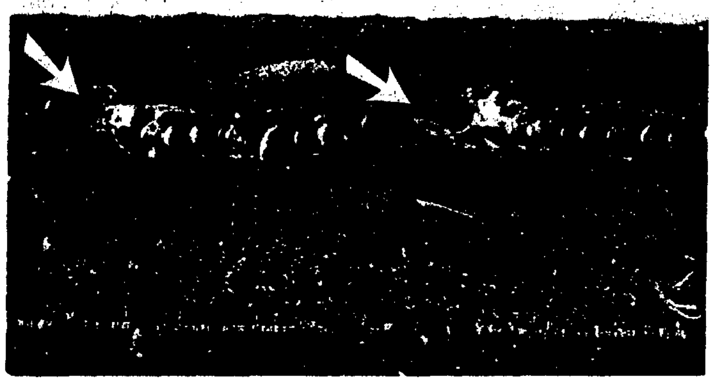
5.4.3. Weld skips. A typical weld skip is shown in Figure 37. They were usually about 0.01 inches long, readily detectable at 10X magnification, but not visually. They were subsequently eliminated by modifying the computer program for the laser weld track so that the various weld segments forming the joint do not terminate prematurely and hence fair into each other.

5.4.4. Fissures. All observed fissures were located at the weld centerline on the weld underside as shown in Figure 38. They are attributable to low-melting segregates produced by excessive weld travel speeds. They were 0.0002 inches wide and up to 0.5 inches long, but no depth was discerned by metallographic examination of cross sections at 300X magnification. They were easily detectable at 20X magnification, but not detectable by visual and fluorescent penetrant inspections.



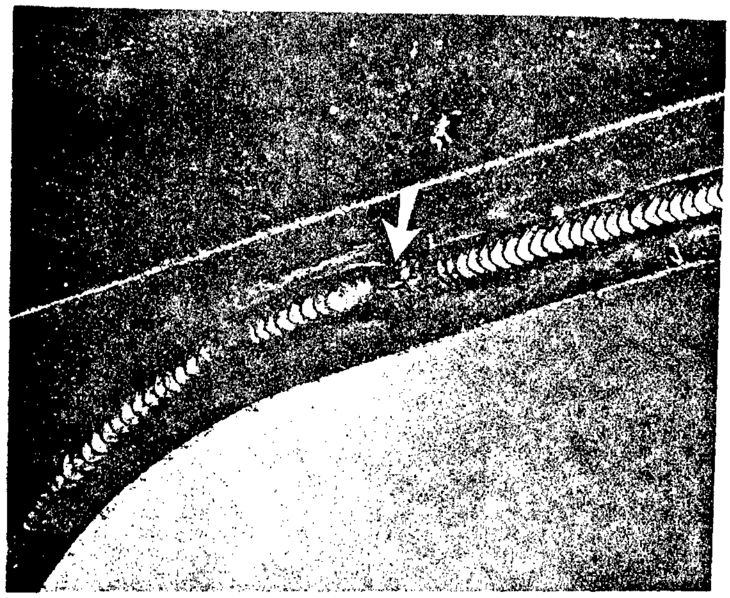
MAG:10X

Figure 35
WELD UNDERCUTTING

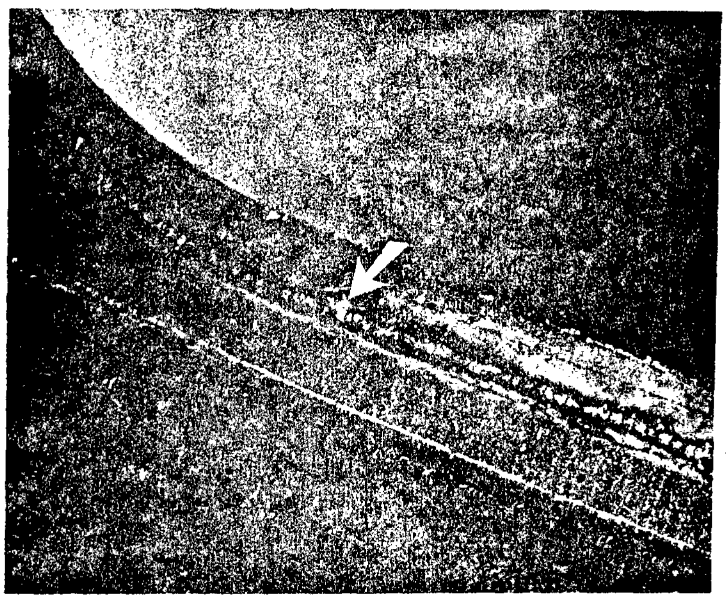


MAG: 10X

Figure 36
WELD MELT THROUGH

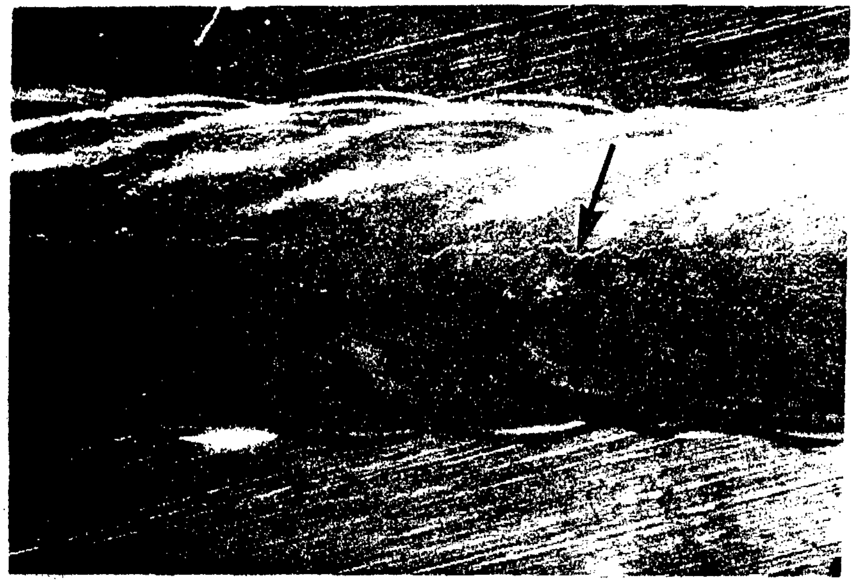


Weld Top Surface - Mag 10X

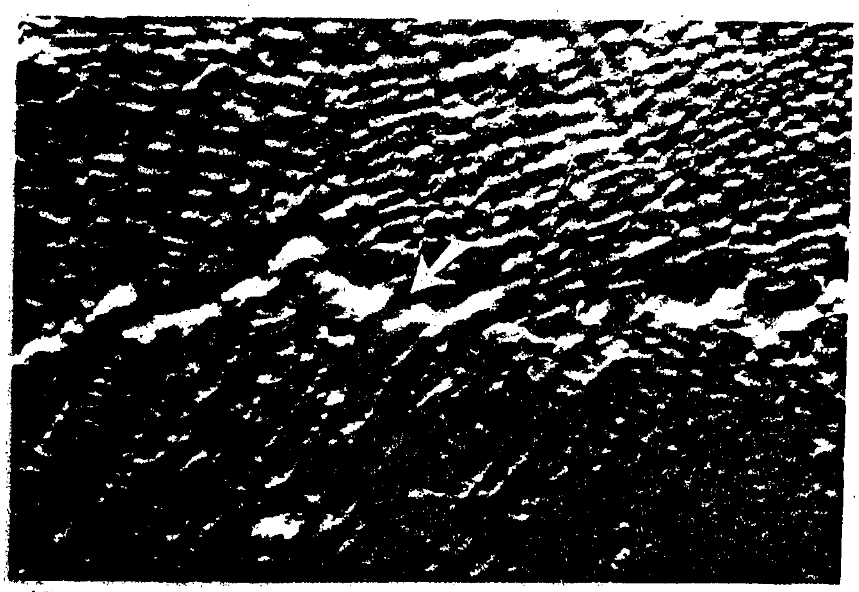


Weld Underside Surface - Mag 10X

Figure 37
REPRESENTATIVE WELD SKIP



Mag: 120X



(Scanning electron microscope photomicrograph)
Mag: 1200X

Figure 38
REPRESENTATIVE WELD FISSURES

5.4.5. Welds deviated to the plate edge. Figure 39 is photomacrographs showing this type of anomaly. Generally, the weld width was not greatly diminished when the weld was deviated to the plate edge. However, in one joint it was reduced to about 20 percent of the normal width in some areas, as shown in Figure 5. This condition was more easily detectable at 10X magnification than visually. This anomaly can not occur when hole side tooling is used, as in the production faculty.

5.4.6. Incomplete penetration. Figure 40 shows typical incomplete penetration. This condition was usually intermittent and is attributable to insufficient contact between the joint mating surfaces. This anomally was frequently found where there was undercutting. This condition is readily detectable visually. Twenty-five paired plates containing typical laser weld anomalies were degreased in trichloroethane vapor and resistance seam welded at the I.D. and O.D. joints into an assembly. None of these plates, however, had undercut areas with no weld or fusion at the joint interface or any through-thickness undercut at the weld inner edge. This subsize assembly was pressure tested as required for production recuperator core assemblies. The results were compared to pressure drop acceptance limits for a normal size production assembly, which consists of approximately 300 paired plates. The results were well within the acceptance limits, even when they were multiplied by a factor of 12, which is derived from dividing the number of plates in a standard assembly by the number of plates in the subsize laser welded assembly tested. No leakage was detected in the actual assembly.

Based on the nature of the weld anomalies and the pressure test results described above, the following acceptance standards were developed for the production regenerator plate laser welds:

1. The weld shall blend into adjacent base metal in gradual smooth curves and have reasonably smooth surfaces.

2. The weld shall penetrate through the full joint thickness.

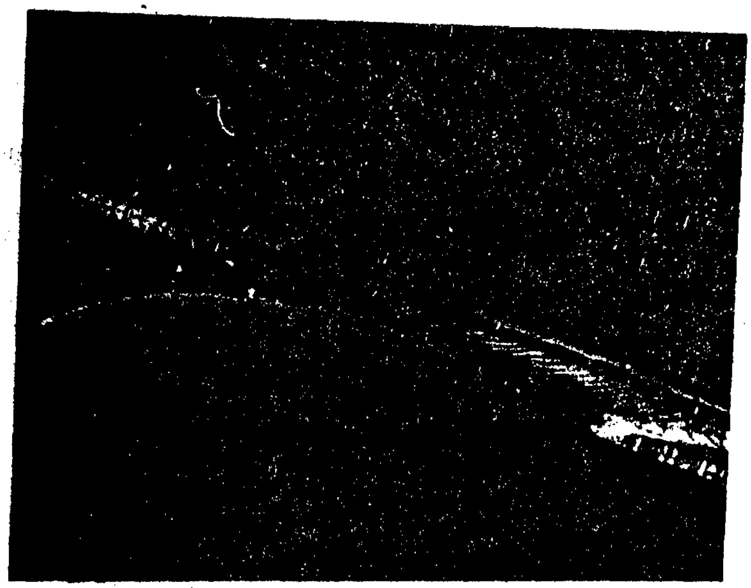
3. The weld shall have:

    a. No undercutting as shown in Figure 35

    b. No melt-through holes as shown in Figure 36

    c. No incomplete penetration as shown in Figure 40

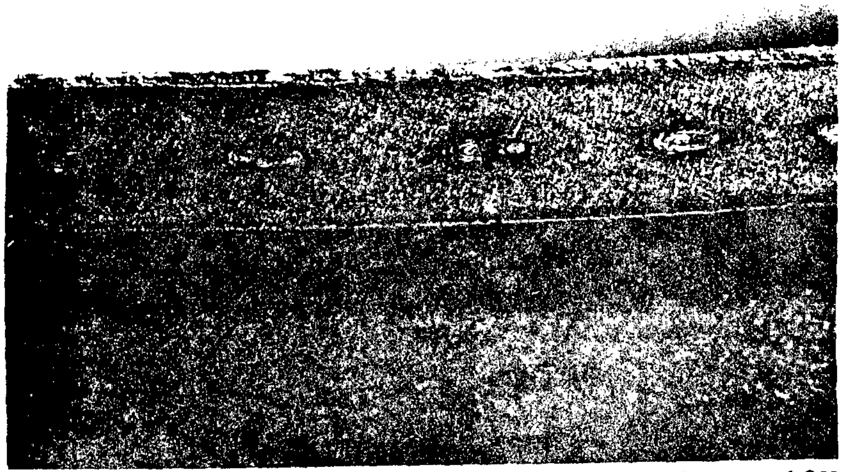
    d. No cracks. However, fissures as shown in Figure 38 are acceptable.



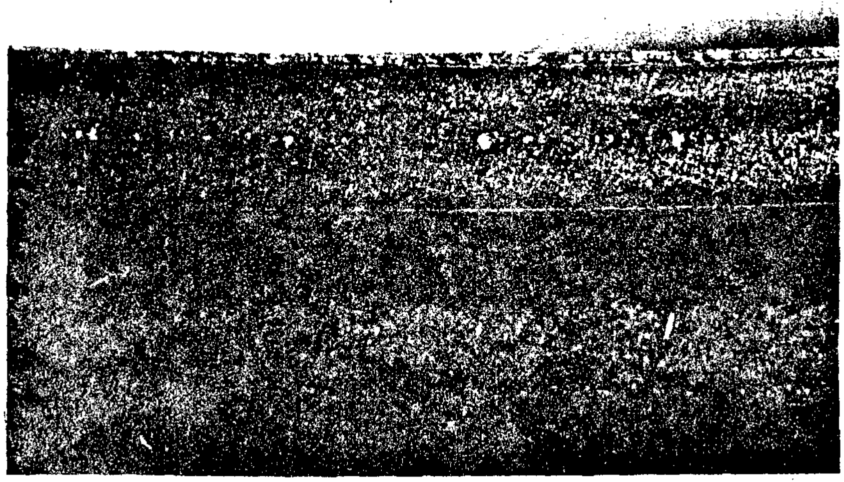
Mag: 10X

Mag: 10X

Figure 39
WELD DEVIATED TO PLATE EDGE



Mag: 10X



Mag: 10X

Figure 40
UNDERSIDE OF JOINT SHOWING REPRESENTATIVE
INCOMPLETE WELD PENETRATION
MAG: 10X

## 6.0. COST ANALYSIS: LASER VS. RESISTANCE SEAM WELDING OF RECUPERATOR AIR HOLE JOINTS

### 6.1 Basis of Comparison.

This analysis compares the two laser automated system, as built, with the automatic dial feed resistance machines now in operation. The costs for one eight-hour shift of operation were determined and totaled for each system; these totals and the production capability of the equipment were then used to calculate the cost of welding one recuperator. These capacity figures should not be confused with the average production rate of equipment which is affected by a number of factors which are difficult to quantify. These include, opeerator efficiency and avalability, detail part availability, availability of maintenance personnel and spare parts, etc. Since this is a cost comparison, the use of capability for both systems has no effect on the final result.

### 6.2 Resistance Seam Welding Costs.

6.2.1. Production rate. Production recuperators are currently welded around the hole joints by two dial feed machines. Each of these has seven resistance welders, arranged around a ten foot diameter indexing table upon which are eight plate holding fixtures. Each welder performs a segment of a joint. The large table indexes the plates from welder to welder and the plate holding fixtures index from hole to hole. Each dial feed welds on average 300 plates per 20 hour day. Thus, together they produce 240 plate pairs per eight-hour shift. There are 280 plate pairs per recuperator.

6.2.2. Costs of labor. Each dial feed machine has a full-time operator in attendance. In addition, another employee works full-time dressing the electrodes for these machines and for the five machines which weld the inner and outer recuperator joints. An analysis of this employee's activity showed that 50 percent of his time was spent on dial feed electrodes.

The dial feed machines, therefore, require 2.5 full time employees. The cost of labor was assumed to be $40.00 per hour. The total labor cost is, therefore, $800.00 per shift and $933.33 per recuperator.

6.2.3. Cost of electricity. In order to determine the exact cost of electrical power for the dial feeds, the amperage being drawn on each of the two input buses of an operating machine was measured. One of these inputs is on constantly while the other feed current 75 percent of the time. Hence, different duty factors are used in the calculation. The phase factor for the three phase, 480 volt system is 1.73. Electricity currently costs $0.085/kilowatt hour.

The cost of electricity to operate the two dial feed stations for one shift is, therefore, $20.72 and the electricity to weld the hole joints for one recuperator costs $24.17.

6.2.4. Cost of water cooling. Each dial feed system uses 35 gallons per minute of cooling water. It runs continually. In an 8 hour shift the two systems therefore use 33,600 gallons. At $3.60 per 10,000 gallons this cost is $12.01 per shift and $14.11 per recuperator.

6.2.5 Cost of electrodes. Each of the seven resistance welders which make up a dial feed machine has special copper electrodes designated for the segment of weld joint it produces. These electrodes wear as they roll across the recuperator plates and must be periodically machined to the proper contour. This is done twice per shift. After about fifty remachinings, the electrodes are too small and are discarded. A set of new electrodes costs $600.00 per dial feed. Therefore, the cost of electrodes for two dial feeds is $48.00 per shift and $56.00 per recuperator.

6.2.6 Cost of maintenance and repair. The dial feeds currently average about 50 percent downtime for maintenance and repair. There are presently six maintenance people permanently assigned to the recuperator line on the first shift and two on the second shift. A significant amount of their time is spent on the dial feeds. It is however difficult to quantify this cost because the number of people and trades required depends on the specific problem being addressed. This cost could be as high as 100 man hours per week.

This cost was not included in the final tabulation for three reasons:

1. It is intended to make this cost calculation as objective and conservative as possible.

2. The maintenance & repair costs of the new dial feed now being delivered could be significantly lower

3. The maintenance and repair costs of the laser system, while expected to be much less because of its greater mechanical simplicity are as yet unknown.

6.3. Laser Welding Costs.

6.3.1. Production rate. The laser welding system as presently programmed, is capable of welding about 245 plate pairs per 8 hour shift. As operator proficiency and more experience with the system are acquired it may be possible to eliminate or shorten certain pauses and holds in the program, thus increasing this rate. (A reduction of six seconds per plate pair increases the per shift rate by twelve pairs). At a 90 percent utilization factor, based on 240 pairs in eight hours, (the guaranteed minimum capability) the rate is 216 plate pairs per shift. This minimum rate was used in this cost analysis.

6.3.2 Cost of labor. The production system has two lasers serviced by one load/unload device, all within a single enclosure. It is designed to be serviced by one operator. The cost of labor is, therefore, $414.72 per recuperator.

6.3.3 Cost of electricity. The two lasers use 5 kilowatts while on standby during the 10 percent of each shift devoted to start up, housekeeping, and maintenance; 8 kilowatts hours are used in this way per shift. While welding, each laser uses 10 kilowatts per hour. Therefore, 144 kilowatt hours is used per recuperator by the two lasers.

Each laser has a heat exhanger which uses one kilowatt, and runs eight hours per shift, thus using an additional 16 kilowatt hours.

The computer and associated control circultry use about one kilowatt, hence 8 kilowatt hours per shift. The cost of electricity is, therefore, $19.38 per recuperator.

6.3.4. Cost of water. The laser systems use closed loop cooling with built-in chillers which exhaust waste heat into the air. The electricity to operate these has been included above. There is, therefore, no water cost.

6.3.5. Cost of gases. The two lasers each use 3.0 cubic feet per hour of a gas mixture which is 13.5 percent nitrogen, 4.5 percent carbon dioxide, and 82 percent helium. Therefore, the two lasers use 4.8 cubic feet in eight hours. This mixture is bought premixed for $.22 per cubic foot. The cost of laser gas is therefore $13.82 core.

In addition to laser gases shielding of the joint area is required. Presently the top of the plate is being shielded with helium and the underside with argon while welding. About 160 cubic feet per shift of helium and about 60 cubic feet of argon are used. Helium costs $.12 per cubic foot and argon costs $.07 per cubic foot. Therefore helium cost $24.88 per core and argon costs $7.26

The total cost of all gases is $45.95 per recuperator.

## 6.4. Cost Comparison: Resistance VS. Laser Welding.

| | Resistance Welding | Laser Welding | Difference |
|---|---|---|---|
| Labor | 933.33 | 114.72 | 518.61 |
| Electricity | 24.17 | 19.38 | 4.79 |
| Water Cooling | 14.11 | ... | 14.11 |
| Electrodes | 56.00 | ... | 56.00 |
| Gases | ... | 45.95 | 45.95 |
| TOTAL | 1027.60 | 480.05 | 547.56 |

## 6.5. Discussion.

Cost of labor is the largest single cost difference between the two systems. This is readily explained: The two dial feed machines are separate, parallel operations, each requiring an operator. The laser facility, although involving two lasers, is a single integrated system with both lasers and the single load/unload device which services them all within one enclosure. This enclosure is smaller than either dial feed machine. Only one operator is required for the entire laser system.

Cost of electricity for the two systems are much closer than might be expected. It is surprising that one could operate two dial feed machines with their fourteen resistance welders and two large and sixteen small rotating tables for a per recuperator cost about the same as two 525 Watt lasers and their much simpler work handling systems. The reason is that resistance welding is at least twenty times more electrically efficient than laser welding and that, although there are fourteen resistance welders, the total weld length made is the same for either system. On average, each resistance welder operates for only one-seventh the time that each laser welder runs.

# 7.0 DESCRIPTION OF PRODUCTION LASER WELDING FACILITY DEVELOPED AND CONCLUSIONS

## 7.1 Description of Production Recuperator Laser Welding Facility Developed and Built in This Program.

Appendix C is the specification for quotation for the production system

The production recuperator welding machine has two 525 Watt pulsed $Co_2$ lasers with moving mirror systems, controllers, rotary positioning tables and fixtures, and a swing arm load/unload mechanism shared between the two laser stations. Figure 40. The welders run out of phase so that while one laser is welding, the other is being unloaded and then loaded. This allows the load/unload mechanism to be time-shared but provides maximum redundancy in the more complex portions of the system. Figures 41 and 42 show the system.

Two lasers, each welding at eighty to one hundred inches per minute, are needed in order to join the large volume of plate pairs required by the production schedule. Each laser has its own moving mirror and computer system as well as a complete tooling package. When the system was being designed, it was suggested that each laser weld five hole pairs on each plate, thus saving one indexing table. This would provide no true system redundancy. The lasers would be so close together that it would be impossible to repair most parts of one while the other was running. The use of separate indexing and tooling packages provides a system which can run at 50 percent through-out while being serviced.

The lasers themselves, are identical to the equipment used to weld the plates for the two engine test cores as described in Chapters II and III.

The Anorad computer used in the development phase was not used on the production machine. The Allan Bradley 7100 was selected because it provides the capacity needed to control the various fixture and load/unload functions, and is common to many of Lycoming's machine tools. This simplifies parts inventories and service.

The machine has seven axis of motion; X & Y on each moving mirror system, a rotary stage for indexing in each welding station and the robot rotary stage . All use the same motors, encoders and tachometers. All are connected by identical plug connectors. This greatly simplifies trouble shooting, and spare parts inventory.

Strickly speaking, the load/unload device is not a robot, for it has no controller of its own. When in operation it is controlled by the computer whose work station it is loading or unloading.

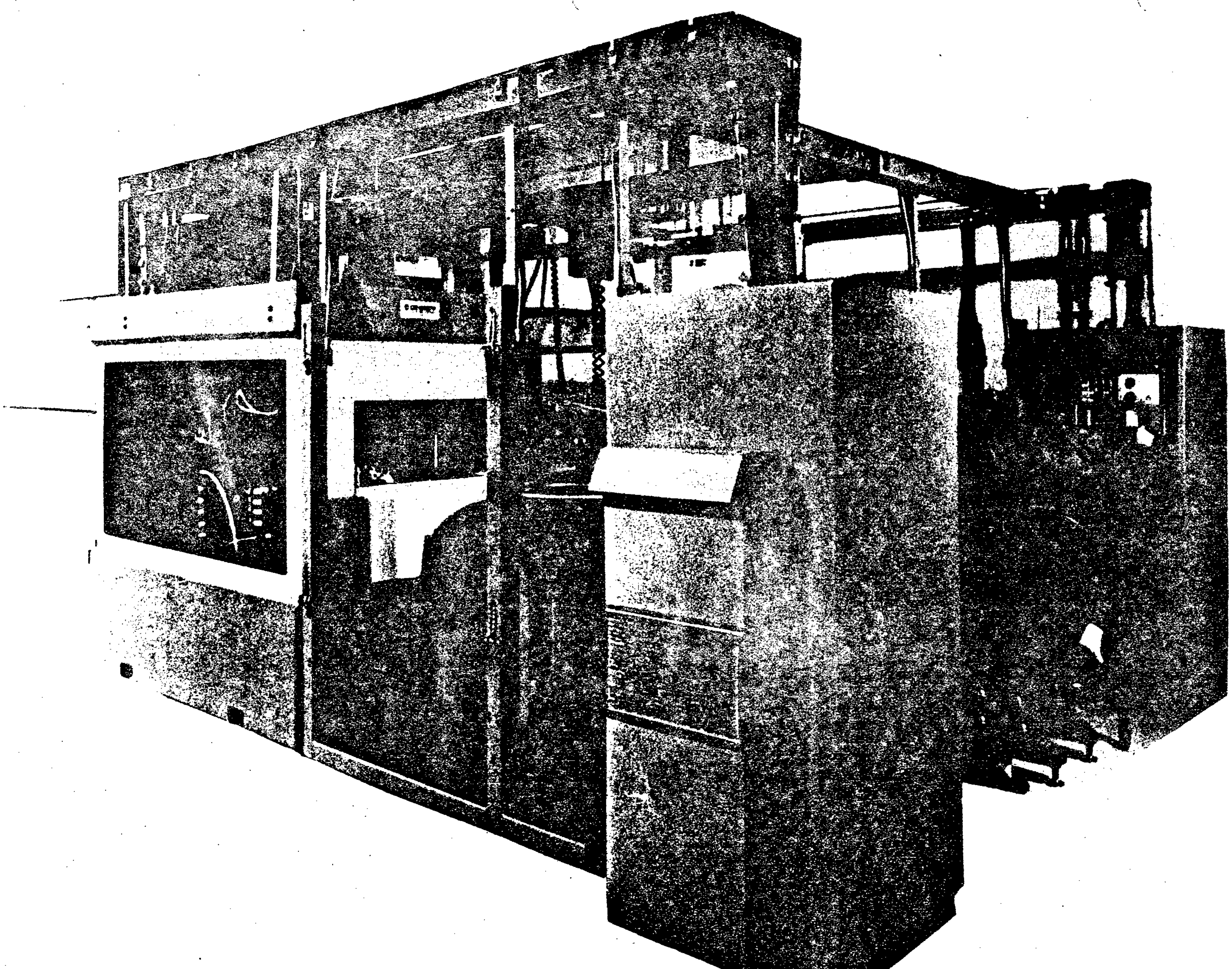


Figure 41. PRODUCTION RECUPERATOR LASER WELDER

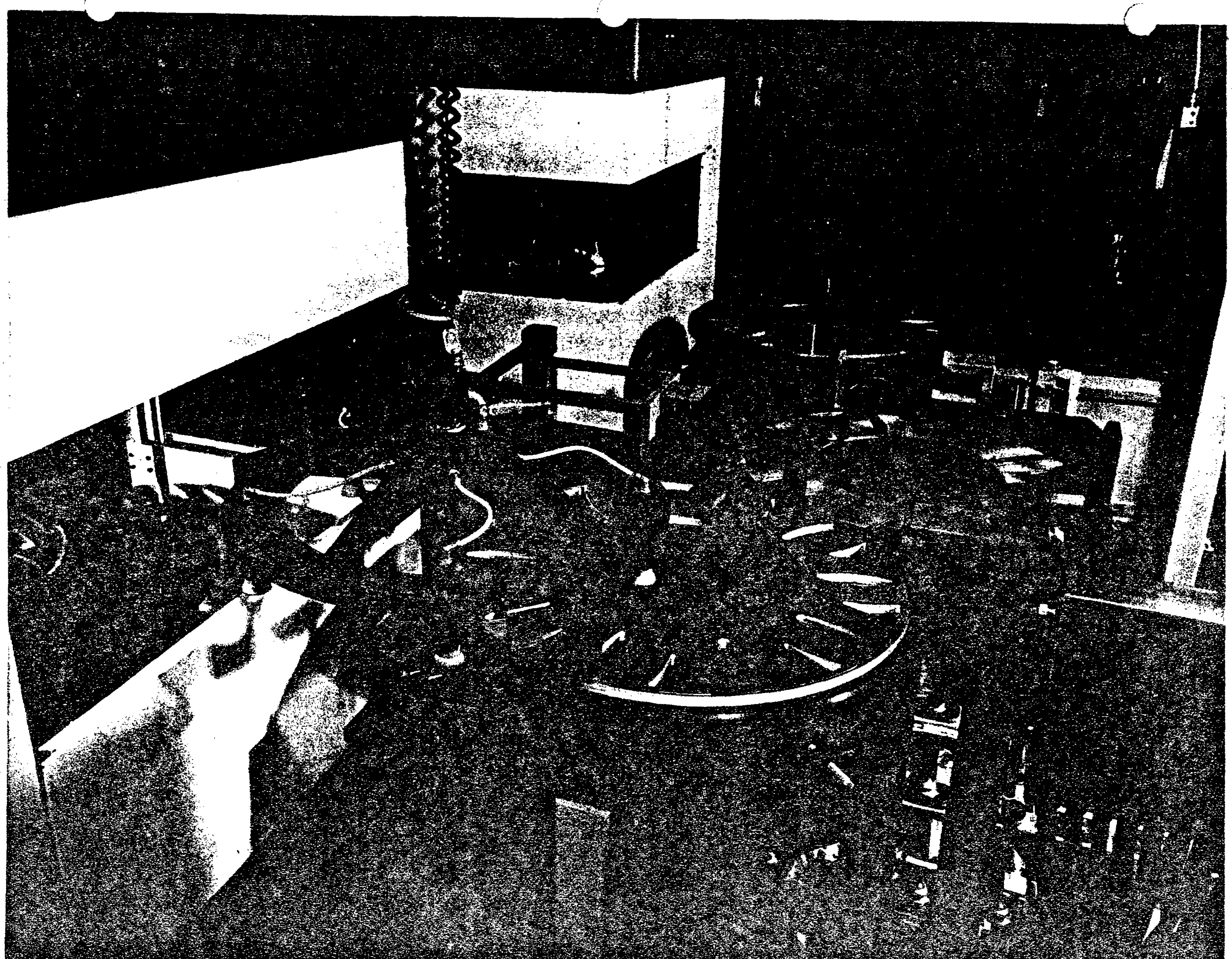


Figure 42. PRODUCTION RECUPERATOR LASER WELDER

## 7.2 Conclusions.

### 7.2.1. Lasers.

- o Energy density at the surface of the material to be joined is critical to laser welding applications. Precise control of output mode and the ability to produce high instantaneous energy density by pulsing reduce total energy input required for a given weld and hence reduce part distortion.

- o In order to insure output stability, a method of mounting the components of the laser cavity which eliminates thermal distortion is absolutely essential, as is a stabilized, closed loop design for the electrical system which produces the glow discharge.

- o Helium neon auxiliary lasers are not acceptable alignment devices for carbon dioxide welding lasers with moving mirror systems.

### 7.2.2. Computer systems.

- o The electrical isolation of the various subsystems of the laser from the computer is absolutely essential to the operation of computer controlled laser systems.

- o A system with program inputs through a CRT/keyboard or PROM or magnetic tape is superior to one using paper tape and a mechanical teleprinter.

- o The computer must be able to calculate displacements and corrections from program and mirror system inputs in real time. Therefore, it must have a hardware clock and an Arithmetic Logic Unit (ALU) with high speed hardware multiply and divide.

- o Computer programs for tracking joints to be laser welded must have no uncontrolled corrections at the intersections of arc segments or straight lines. Weld defects will occur unless these transitions are smooth and step-free.

- o Cross-section macro inspection of welds made with computer controlled lasers are, alone, inadequate to assure defect-free welds. Welds must also be sectioned and peeled and inspected parallel to the direction of beam travel.

### 7.2.3. Moving Mirror Systems.

- o Commercially available moving mirror systems operate with the precision and dependability required for this application.

- Gallium arsenide output lenses are superior to potassium chloride lenses because they are less hydroscopic and less susceptible to thermal runaway.

7.2.4. Tooling.

- The tooling system using stationary hole side tooling under the laser beam track and indexing the recuperator plates between hole pairs is clearly superior for this application.

7.2.5. Cost analysis and program return on investment

- The developed laser system is capable of welding the hole joints of one recuperator core for over $500 less than the currently used resistance welding facility of equal capacity.

- The total cost savings attributable to this program from reduced manufacturing costs over a 7000 engine buy, if only one laser facility is required to meet production schedules, is $3,500,000

- This program provided the recuperator manufacturing department with a laser welding facility of capacity equivelant to at least one and one half dial feed machines. A dial feed currently costs $1,100,000. A laser machine similar to the one provided is now priced at $1,200,000.

The B.O.C. laser system, procured in Phase I, has been sent to the U.S. Army TACOM Materials Laboratory, Warren, Michigan, for use on other development programs. When procured in 1977 it cost $157,000. Since its current valve is unkown it is not included in the calculation of return on investment. However, it is obviously a substantial asset to the U.S. Army.

- The total cost of this program to the U.S. Army was $318,000 for Phase I and $1,260,000 for Phase II.

- The program return on investment is therefore:

| | |
|---|---|
| Cost Reduction @ $500 per engine | $3,500,000 |
| Reduced capitol equipment costs (1 1/2 Dial Feed Machines) | $1,600,000 |
| An experimental laser facility provided to the Army at no cost. | ---------- |
| Less total cost of program | $1,600,000 |
| Savings resulting from program | $3,500,000 |

7.2.6. General conclusions.

- The replacement of resistance seam welding by computer controlled laser welding in the manufacture of AGT 1500 recuperator air hole periphery joints is technically feasible and cost effective.

- The laser welded recuperator is functionally equal to the resistance welded one as shown by engine testing and metallurgical evaluation of the welds.

## BIBLIOGRAPHY


### Books

Duley, W. W. 1976. $CO_2$Lasers. New York: Academic Press.

Ferris, S. D., Leamy, H. J. and Poate, J. M., Eds., 1979. Laser-Solid Interactions and Laser Processing - 1978. New York: American Institute of Physics.

Harrington, J. 1973. Computer Integrated Manufacturing. New York:

Kearns, W. H., ed., 1980. Welding Handbook. Vol. 3. Miami, FL: American Welding Society.

Mauren, R. E. Laser heat treatment of bearing races. Interim Technical Report, U.S.A.F. Material Laboratory, Wright-Patterson Air Force Bases, 1 Oct to 31 Aug, 1980.

Ralst, A. and Meek, C. 1976. Encyclopedia of Computer Sciences. New York: Pretrocelli/Charter.

Savas, E. S. 1965. Computer Control of Industrial Processes. New York: McGraw-Hill Book Company.

Weast, R. C., Ed., 1979. C.R.C. Handbook of Chemistry and Physics. Boca Raton, FL: CRC Press, Inc..

### Journals

Anonymous. 1977. Welding with Lasers. Electro-Optical System Design, 9(3):29-32.

Anonymous. 1979. Laser welding speeds relay production. Insulation Circuits, 25(4):24-25.

Anonymous. 1980. Welding in the 80's - Robot control and micro processor-based systems are expected to change the welding scene of the next decade. Engineering Materials and Design, 24(9):22-7.

Baarden, E. L. et al. 1973. High speed welding of sheet steel with $O_2$ laser. Welding Journal, 52(4):227-9

Balatskii, A. A. and Igumnov, V., and Baranov, M. S. 1973. Photo-electronic device for searching the weld area in laser welding. Welding Production, 20(122):29-30.

Cline, H. E. and Anthony, T. R. 1977. Heat treating and melting material with a scanning laser or electron beam. Journal of Applied Physics. 48(9): 3895-3900.

Engel, S. L. 1978. Metal working with yag. Laser Focus, 14(12):66-8.

Jefferson, T. B. 1980. Computer run machine welds blades and vanes. Welding Design and Fabrication, 53(3):90-92

Klemens, G. G. 1972. Heat balance and flow conditions for electron beam and laser welding. Journal of Applied Physics, 47(5):2165-2174.

Mishima, Y. and Murakimis., 1979. Automobile body assembly line system based on module type robot application. Industrial Robot, 6(4):206-214.

Morgan-Warren, E. J.1979. The application of laser welding to overcome joint asymmetry. Welding Journal, 58(3):765-825

Raamot, J. and Jablonski, D. 1977. Complimentary control of scanner gives 0.0 percent accuracy in laser beam deflection. Laser Focus, 15(5):96-100.

Robinson, C. A., Jr. Feb. 23, 1981. Advance made on high energy laser Aviation Week and Space Technology. 25-27.

Robinson, C. A., Jr. Feb. 16, 1981. Laser technology demonstration proposed. Aviation Week and Space Technology. 16-19.

Seretsky, J. and Ryba, E. 1976. Laser welding of dissimilar metals: Titanium to nickel. Welding Journal, 55(7):2085-115.

Spynu, G.. A. et al. 1977. Arc welding with an industrial robot using a program prepared with the aid of a computer. Automatic Welding, 30 (12):24-28.

Wetmore, W. C., October 8, 1979, Research center explores capabilities of advanced industrial lasers. Aviation Week and Space Technology, 62-67.

Young, A., 1978, Welding and drilling with pulsed lasers. Metal Construction, 10(1):34-35.

# APPENDIX A

# LITERATURE SOURCES SEARCHED

## APPENDIX A

## Literature Sources Searched

Sources Searched by Computer:

- USG - National Technical Information Service
- World Aluminum Abstracts
- Mechanical Engineering ( ISMEC )
- Metals Abstracts ( AS 14 )
- Engineering Index
- INSPEC
- Conference Papers Index
- Energy Abstracts
- WELDSEARCH

Abstract Lists Reviewed:

- Computer and Control Abstracts, Institute of Electrical Engineers 1973-1980

- Citations from the Engineering index on Laser Welding, 1970 - August 1979.

# APPENDIX B

## SPECIFICATION FOR NICKEL BASE ALLOY, SHEET, CORROSION, AND HEAT RESISTANT (INCONEL 625)

## APPENDIX B

### SPECIFICATION FOR
### NICKEL BASE ALLOY, SHEET, CORROSION, AND HEAT RESISTANT
### (INCONEL 625)

1. SCOPE. This specification covers the chemical, mechanical property and inspection requirements for sheet stock of this alloy (see 6.1).

2. APPLICABLE DOCUMENTS. The following documents of the issue in effect on date of invitation for bids or requests for proposal, forms part of this specification to the extent specified herein.

SPECIFICATION

Society of Automotive Engineers

| | |
|---|---|
| AMS 2262 | Tolerances - Nickel, Nickel-Base, and Cobalt-Base Alloy Sheet, Strip, and Plate |
| AMS 2269 | Chemical Analysis Check Limits - Wrought Nickel and Nickel Base Alloys |
| AMS 2371 | Quality Assurance Sampling of Corrosion and Heat Resistance Alloys Wrought Products Except Forgings |

STANDARDS

American Society for Testing and Materials

| | |
|---|---|
| ASTM E8 | Tension Testing of Metallic Materials |
| ASTM E112 | Estimating Average Grain Size of Metals |
| ASTM E139 | Conducting Creep and Time - for Rupture Tension Tests of Materials |

3. REQUIREMENTS

3.1. General material requirements.

3.1.1. Character or quality.

3.1.1.1. Condition. Unless otherwise specified on the purchase order, the material shall be delivered cold rolled and bright annealed.

Note The annealing temperatures shall produce the tensile requirements specified herein.

3.1.1.2. Quality. The material shall be uniform in quality and condition, clean, sound and free from foreign materials and from internal and external imperfections detrimental to fabrication or performance of parts.

3.1.2. Product characteristics.

3.1.2.1 Thickness. This specification covers this material up to 0.020 inch (0.51 mm) thick.

3.1.2.2 Tolerances. Unless otherwise specified on the purchase order, tolerances shall conform to all applicable requirements of AMS 2262.

| | Min | Max |
|---|---|---|
| Carbon | -- | 0.10 |
| Manganese | -- | 0.50 |
| Silicon | -- | 0.50 |
| Phosphorus | -- | 0.015 |
| Sulphur | -- | 0.015 |
| Chromium | 20.00 | 23.00 |
| Molybdenum | 8.00 | 10.00 |
| Columbium and Tantalum | 3.15 | 4.15 |
| Iron | -- | 5.00 |
| Cobalt (see note) | -- | 1.00 |
| Titanium | trace - | 0.40 |
| Aluminum | trace - | 0.40 |
| Nickel | | remainder |

Note: Determination not required for routine acceptance

3.1.3.1.1. Check analysis. Composition variations shall meet the requirements of Specification AMS 2269.

3.1.3.2. Tensile properties. The tensile properties shall be as follows:

| | Psi | mPa |
|---|---|---|
| Ultimate strength, min | 105,000 | 724 |
| Yield strength at 0.2% | 48,000 min<br>57,000 max | 331 min<br>393 max |
| Elongation, % in 2 in., min | 35 | 15 |

3.1.3.3. Stress rupture. A tensile test specimen maintained at a temperature of 1500 $\pm 5^{o}F$ (815.6 $\pm 2.8^{o}C$) while an axial load 16.500 psi (113.7 MPa) is continuously applied shall not fail in less than 23 hours and a elongation shall be not less than 15 percent in 2 inches.

3.1.3.4. Bending. The material shall withstand, without cracking, bending at room temperature through an angle of 180 degrees around a diameter equal to the nominal thickness of the material, with the axis of the bend parallel to the direction of rolling.

3.1.3.5. Grain size. When the specimens are measured in accordance with Standard ASTM E112, the grain size shall be ASTM #5 or finer.

3.1.3.6. Surface oxidation. Unless otherwise specified, there shall be no evidence of surface oxidation present on the product.

3.1.3.7. Weldability. Welded test specimens shall meet all of the requirements specified on the engineering drawing for resistance welds for assemblies made of this alloy.

3.1.4. Identification and marking. When identification marking is performed directly on the material, the marking fluid shall have no deleterious effect on the material and shall be sufficiently stable to withstand normal handling. The marking fluid shall be capable of being removed in a hot alkaline solution. Unless otherwise specified on the purchase order, the sheet shall be marked on one face as follows:

a. Rows of characters spaced not over three feet (914 mm) apart

b. Characters shall be of a size to be clearly legible.

c. Marking shall include the following: M3622, revision letter, heat number, manufacturer's identification and nominal thickness.

3.1.4.1. Flat sheet over 6 inches (152 mm) in width. Flat sheet, over 6 inches (152 mm) in width shall be marked in lengthwise rows of characters. The rows of characters shall be spaced not more than 6 inches apart and alternately staggered.

3.1. Coiled sheet. Coiled sheet shall be marked near the outside end of the coil. The insider end of the coil shall also be marked or shall have a tag or label attached and marked with the same information.

4. QUALITY CONTROL ASSURANCE PROVISIONS

4.1. General.

4.1.1. Responsibility for inspection. Unless otherwise specified in the contract or purchase order, the supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any other facility acceptable to the procuring activity. The procuring activity reserves the right to perform or witness any of the necessary tests to assure that incoming material conforms to the requirements of this specification.

4.1.2. Specimen orientation. Tensile test specimens taken from widths 9 inches (229mm), tensile test specimens shall be taken with the axis of the tensile specimen parallel to the direction of rolling.

4.1.2.1. Proprietary information. Any of the processing control factors considered proprietary by the vendor may be assigned a code designation. Each variation of such factors shall be a modified code designation.

4.1.3. Process control data. The vendor shall establish the control factors for production processing which will produce sheet material acceptable to the property requirements specified in 3.3. These control factors shall constitute the approved procedure and shall be used for producing production sheet material. If necessary to make any change in control factors of processing, the vendor shall submit for reapproval a statement of the proposed changes in processing and sample test specimens. Production sheet material incorporating the revised operations shall not be shipped prior to receipt of reapproval.

4.1.4. Certification. Unless otherwise specified on the purchase order, the supplier shall furnish 3 copies of a certificate with each shipment stating the following information:

a. Purchase order number.

b. Size or part number and change letter.

c. Quantity.

d. Material specification designation.

e. Heat number

f. Chemistry.

g. Mechanical properties.

h. Statement of conformance to M3622, latest revision.

4.2. <u>Quality conformance inspection</u>.

4.2.1. Sample tests. Unless otherwise specified on the purchase order, the product shall be sampled and tested in accordance with Specification AMS 2371.

4.3. Test methods.

4.3.1. Chemical analysis. The chemical analysis specimen shall be analyzed to verify conformance to 3.1.3.1.

4.3.2. Tensile properties. Test specimens shall be tested inaccordance with Standard ASTM 8 (ref. 3.1.3.3).

4.3.3. Stress rupture. Test specimens shall be tested in accordance with Standard ASTM E139 (ref. 3.1.3.3).

4.3.3.1. Increased loading. The stress rupture test may beconducted at a load higher than 16,500 psi (113.7 mPA), but the load shall not be changed while the test is in progress. The time to rupture and the elongation shall remain the same (ref. 3.1.3.3).

4.3.4. Grain size. Grain size shall be determined in accordance with Standard ASTM E112 (ref. 3.1.3.5).

4.3.5. Compatability test. When tested, test specimens shallmeet the requirements of 3.1.3.4., 3.1.3.6, and 3.1.3.7.

5. PREPARATION FOR DELIVERY

5.1. Preservation, packaging and packing. The product shall be prepared for shipment in accordance with commercial practice to assure carrier acceptance with commercial practice and assure carrier acceptance and safe transportation to the point of delivery. Packaging shall conform to the requirements of carrier rules and regulations applicable to the mode of transportation.

5.2. Marking. When the product is boxed for delivery, the box shall be permanently and legibly marked with the information specified in 3.1.4.

6. NOTES

6.1. Intended use. This material is intended primarily for partrequiring good corrosion and oxidation resistance a temperatures up to approximately 2000$^{o}$F (1093$^{o}$C), and where such parts may require welding.

6.2. Ordering data. Procurement documents should specify thefollowing:

a. Title, number and data of this specification.

b. Size (length, width, thickness).

c. Quantity.

# APPENDIX C

## SPECIFICATION FOR QUOTATION OF LASER WELDING SYSTEM FOR THE AGT 1500 RECUPERATOR

APPENDIX C

# SPECIFICATION FOR QUOTATION OF A LASER WELDING SYSTEM FOR THE AGT 1500 RECUPERATOR

## I. INTRODUCTION

Avco Lycoming's AGT 1500 gas turbine is a regenerative engine with a multiwave plate recuperator.

This recuperator is made of thin convoluted metal plates welded to form an integral unit containing heat transfer matrices and internal air conduits. The exhaust from the power turbine enters the center of the annular recuperator where it diffuses and turns radially to flow through the heat exchanger. Compressor air enters the air inlet conduits from the front, passes between the plates, and then, via the air exit conduits, leaves at the front of the recuperator. Resistance seam welding is currently used to join the two kinds of convoluted plates.

In assembling the recuperator core, each pair of plates first must be welded around the air conduit cutouts. Next, the pairs are stacked and resistance seam welded around the inside and outside diameters. The welded bellows-like assembly is then attached to a front header plate.

The recuperator is made of 280 "A" plates (P/N 3-500-031-12) and 280 "B" plates (P/N 3-500-032-08) stacked alternately. The plates are formed of Inconel 625 - .008 inch thick, and are annular in shape with inside diameter of 15 inches and outside diameter of 27 inches. The embossed flow passages are .040 inch high on both plate types, but are different in pattern.

There are ten air in and ten air out holes alternately equispaced around the plates. Each hole periphery is an .080 inch flat upon which the laser welds must be made and the tooling required to maintain joint contact must grip.

These twenty periphery joints between 280 pair of plates total almost 1.25 miles of weld per assembly. In order to make this amount of weld, the laser must cycle on and off over 5,000 times. These figures are for one recuperator assembly. This facility is expected to be capable of producing two to three cores per day on a three-shift basis; i.e., to cycle almost 17,000 times per day while producing over three miles of weld. The system quoted must be <u>rugged enough for such service in a production enviroment.</u> The quotation shall describe the system and proposed acceptance test in detail.

The system to be quoted does not necessarily have to be based upon a single laser. If the quoter thinks a system in which two or more lasers welding simultaneously is superior, he should quote such a system, and state his reasons, as well as describing the proposed system completely. The quotation shall give a detailed estimate of operating costs for power, gases, and any other costs. The labor requirements shall be described in detail.

## II. GENERAL SYSTEMS REQUIREMENTS

A. The laser welding system defined here is a complete, turn-key system for welding the recuperator air hole peripheries. It is to be suitable for integration into Lycoming's existing recuperator production line. It shall consist of all equipment,(including heat exchangers), tooling, and software necessary to a task. No special cleaning, other than vapor degreasing and no surface coatings shall be required on the parts to be welded.

B. The system shall be capable of dependably welding at least thirty pairs of plates per hour. It shall index between welds at the highest possible speed consistent with dependable operation. Loading and unloading shall be simple and rapid, and automated. The quotation shall explain the operating cycle and basis of the estimated production rate in detail.

C. The welds produced by the system shall be not less than .010 inch wide at the joint between the two sheets. The upper and lower crowns shall be smooth and blend into the adjacent base metal without undercutting. There shall be no cracks, crack-like indications or blow holes, cross weld skips or pores or any other deleteriours defects.

The accuracy of weld location shall be adequate to assure that parts meeting the engineering drawing tolerances can be welded repetitively without the beam hitting the tooling or running off the joint flat.

## III. SPECIFIC SYSTEM REQUIREMENTS

A. The system shall operate on 460 vac. or 208 vac. 60 HZ. It shall be insensitive to input power variations of $\pm$ 10 percent.

B. With the exception of the input power main switch, no operator's control switch, meter or guage shall carry voltages higher than 120 vac.

C. The system shall have a gas mixer capable of accepting the required gases from standard bottles and controlling the required mixtures with sufficient accuracy for the intended purpose.

D. The system shall be capable of operation in a factory environment at temperatures from $50^{o}$ to $100^{o}F$. It shall be insensitive to relative humidity. If this requirement means that certain parts of the machine must be atmosphere controlled, then the quote should reflect this.

E. The system shall meet all Federal and Connecticut State safety requirements for equipment of this kind.

F. Start up time after overnight shutdown shall be stated in the quotation. The system shall have stabilized by the stated time so no operator adjustments of mirrors, output window, or other laser components are necessary for the remainder of the period of operation.

G. All operator controls shall be mounted on suitable external panels. No operating controls or adjustments shall be located in any cabinet so that a safety lock must be defeated to reach it.

H. Computers shall be Allan Bradley 7000 series. Only those controls requiring operator adjustment shall be readily accessible to the operator. Program editing must be key locked. The quote shall explain what these controls are and how frequently they require adjustment.

# APPENDIX D

# PROGRAM MANAGEMENT

## APPENDIX D

## PROGRAM MANAGEMENT

### 1. INTRODUCTION

There are complex problems in the management of applied technology programs, such as this. The question of just how much of the actual development of advanced manufacturing facilities should be done by the user and how much should be subcontracted is critically important to the success of these programs.

There are a number of ways an advanced manufacturing applications program can be approached. These range from the "turn-key" technique (Figure 41) of selecting a source, signing a contract, and suing him if the delivered system doesn't work, to purchasing or building all of the subsystems and developing the facility oneself. There are a number of more reasonable techniques between these extremes, and it is the purpose of this appendix to describe how the management techniques used on this program evolved, and to recommend an approach which best solves the problems of applications development for advanced and rapidly changing technologies.

<u>Phase I Program Management Approach</u>

Over the years, a number of very successful welding applications programs have been done by Lycoming (Miller, 1977; Miller and O'Connor, 1980). In these, the basic welding system was first selected and procured (Figure 42). When it was delivered to Lycoming's Process Technology Laboratory, the process, tooling,and in some cases, the design of the component to be made were developed. Production equipment was then procured, either new or by transferring the original development laboratory equipment to production. The manufacture of the component by the new process was then begun in the production shop.

The latter approach was used at the beginning of this program in Phase I. An investigation of companies then (1977) making laser equipment was conducted, and B.O.C. was selected as the best available system for the application.

The system ordered was not the complete apparatus required to weld recuperator cores: it included the laser, the moving mirrors, and the computer and software. This supplied everything required, down to the laser output nozzle of the moving mirror. Once the system was delivered, Lycoming intended to develop the necessary tooling for the application. This approach was based on our experience with other manufacturers of high technology welding equipment and their usually limited knowledge of turbine engine materials and welding applications.

The approach had worked well in the past, because both the equipment vendor and Lycoming were dealing with that part of the program about which they knew the most. It also provided Lycoming the opportunity for hands-on experience with the equipment during the application development, which was the basis of later production and equipment maintenance support.

The pace of technical change and improvement has increased substantially in recent years. Unfortunately, so have delivery times and the costs and complexity of equipment. One orders a facility with a promised delivery time of perhaps twelve months. This may increase substantially if it is a new, state-of-the-art application and unforseen problems occur. By the time the facility is finally delivered and debugged, it may no longer be the best available for the application and may, in fact, be obsolete. Such was the case with the B.O.C. system procured in Phase I.

Phase II Program Management Approach

When it was decided, at the end of Phase I, that B.O.C. was no longer the state-of-the-art answer for this application, a different program management technique was proposed. Rather than again select the supposedly best system, based on expert opinions and vendor surveys, order it, and again begin application development, it was decided to do the key portions of the development before ordering the system.

After an extensive survey, it was found that four companies were building computer controlled laser welding systems that might be suitable for the recuperator application. These included B.O.C. and three other companies. Each of the four was awarded a small purchase order to build a simple holding tool for the elliptical hole joint. They used this tool to make sample welds in their applications laboratories. This work provided the background experience necessary for the vendors to prepare two proposals. They first outlined costs, schedules, and techniques to be used in a program to develop a prototype laboratory set-up and use it to weld 350 sets of plates. The second was a budgetary proposal for a production laser welding facility based on what was known at the time.

One potential vendor reached the conclusion, during this early phase, that it was not then feasible for him to participate and did not submit program and facility proposals. Two vendors were chosen from the three remaining and each received a purchase order to design and build the prototype set-up in his applications laboratory and with it weld 350 plate pairs. It was understood that the vendor whose program was most successful would receive the order for the complete production facility.

Discussion

The turn-key system (Figure 43) is basically the same system used for most purchases of equipment throughout industry. It is completely adequate for the procurement of easily defined equipment for well understood manufacturing processes.

The procure-then-develop system (Figure 44) is a modification of the turn-key approach in which an intermediate development step is inserted between the delivery of the equipment and its introduction into production. The inclusion of this step implies that all the technology is not completely understood. For technologies where the equipment is inexpensive and quickly delivered, and the basic process is well understood this technique is probably best. Such programs as new applications of standard processes are usually conducted this way. If the engineering staff knows exactly what is required of the purchased system, and how to specify it, this approach allows them to order it early in the program. Often the tooling or other system components can be built while awaiting delivery of the process equipment. The application development step then consists of assembling the system, debugging it, and qualifying it and the parts it produces.

If, however, the basic process being procured is so new that the requirements are not clearly understood, the system just described has several major disadvantages. Complex manufacturing processes require actual operating experience in order to truly understand them. Such experience is gained only after the system is delivered. Without this experience it is very difficult to sort through the confusing claims of several system manufacturers. Additionally, equipment vendors who have delivered a system and been paid early in a program, have been known to show less interest in resolving problems than those who see a large order at the end.

For these reasons, as equipment complexity, cost, and delivery times have increased, the risks involved in using the procure-then-develop have increased. Therefore the develop-then-procure system was adapted (Figure 45). Its advantages are that the selection of the system is postponed by a two step selection process in which vendors compete to be included in the next phase of the program and are paid for their efforts.

While the work of the selection steps is proceeding in the vendor's applications laboratories, the customer's engineering staff works with the vendor's staff. This is important, because the equipment manufacturer needs the customer's input on the requirements of the product the machine will make and the machine's integration into the total manufacturing sequence. The experience which the customer's staff gains with the process, even in the laboratories of the unsuccessful vendors, is one of the most valuable by-products of the

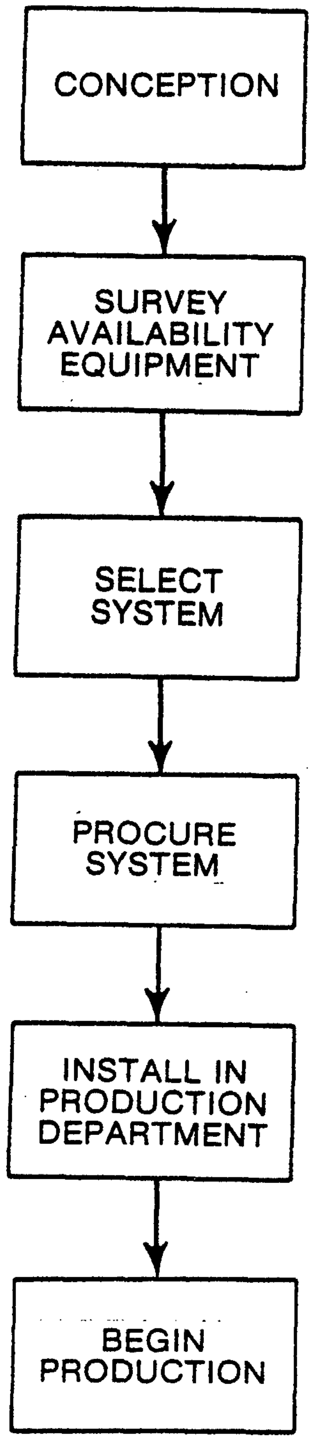



Figure 43
TURN-KEY PROGRAM MANAGEMENT SYSTEM

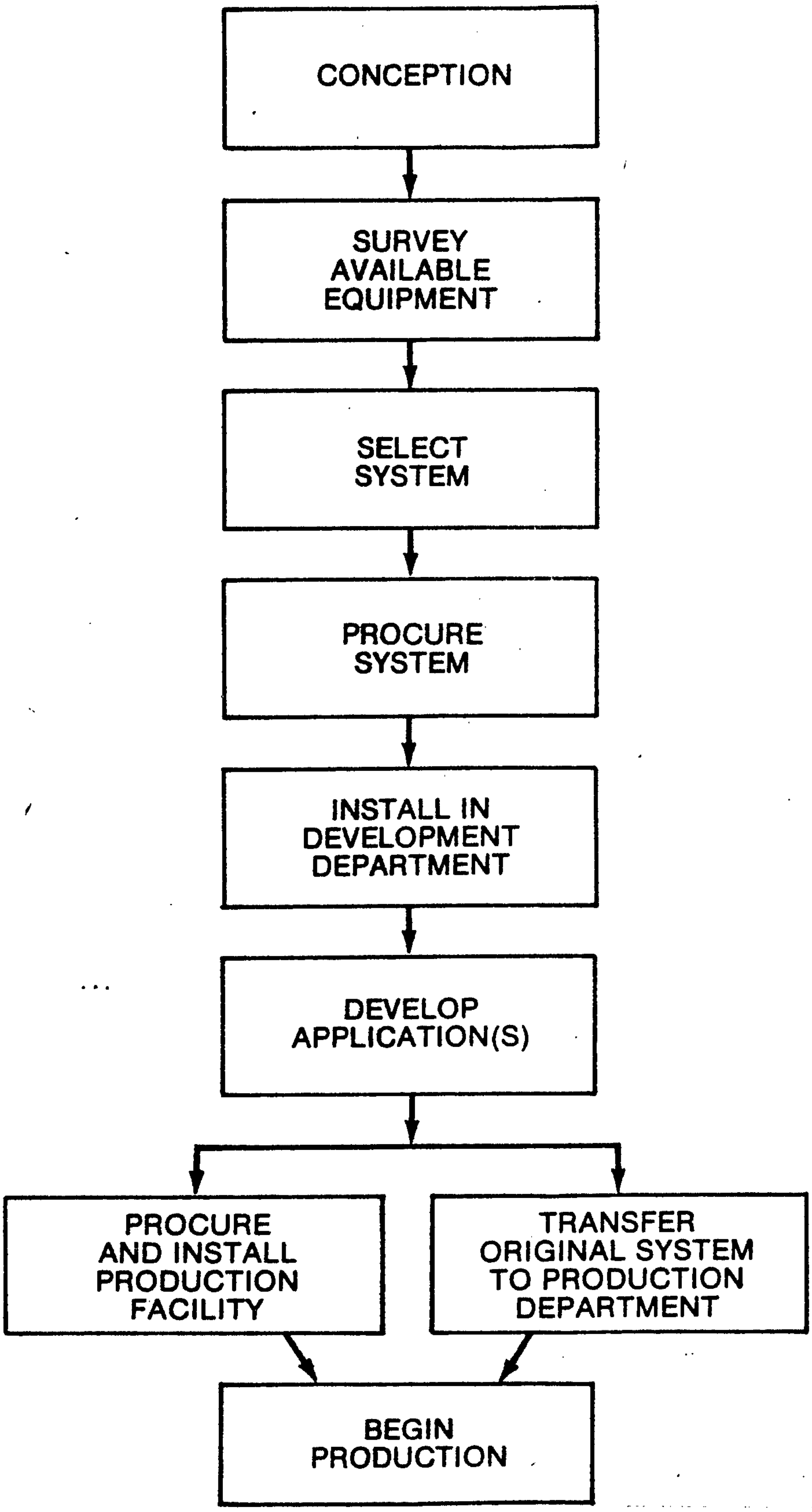



Figure 44
PROCURE-THEN-DEVELOP PROGRAM MANAGEMENT SYSTEM

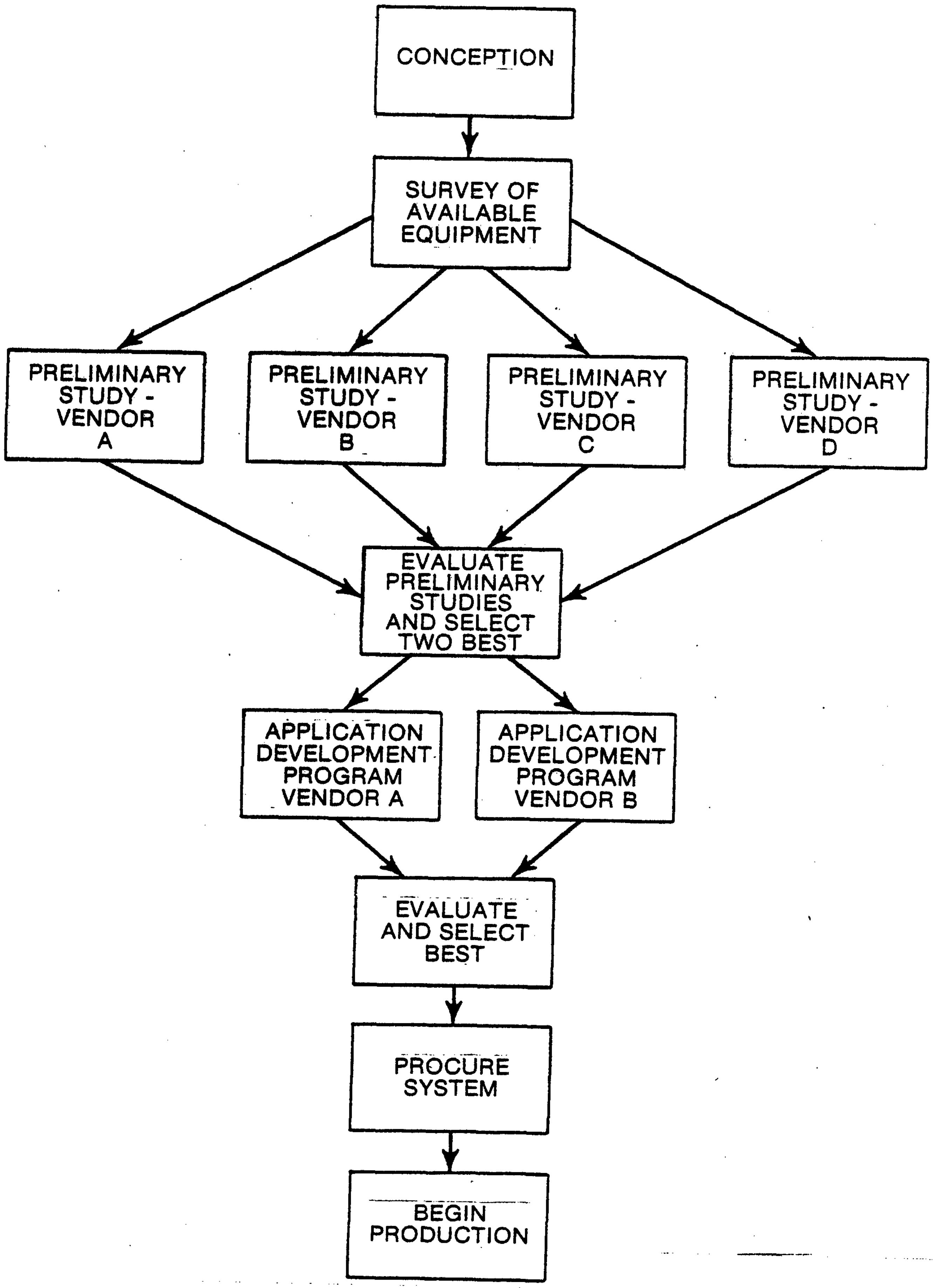



Figure 45
DEVELOP-THEN-PROCURE PROGRAM MANAGEMENT SYSTEM

program. The experience gained with the successful vendor is essential to the customer's ability to operate and maintain the equipment in production.

These selection steps provide the vendor finally selected with the understanding he needs to quote, design, and build the system. Because he has already built and operated a prototype when he quotes the equipment, his estimates of cost and delivery time will be much more realistic than under the former program management system. This means that the time and money spent on the selection steps will probably be recovered by the prompter delivery of a better system than would have otherwise resulted. This was the case in Phase II of this program.

# References

Miller, J. A. 1977. Manufacture of an electron beam welded turbine engine compressor rotor. Welding Journal.

Miller, J. A. & O'Conner, J. J. 1980. Inertia and electron beam welded turbine engine power shaft. Welding Journal.

# APPENDIX E

# REVIEW OF CURRENT LITERATURE

## APPENDIX E

### 1. REVIEW OF CURRENT LITERATURE

The generic topic of this project is computer controlled laser welding, and an extensive literature search on this topic was conducted, early in Phase I in 1976 and again at the beginning of Phase II in 1981. The most recent search is described here. A list of the data bases searched is given in Appendix B. The search of general indexes was done using both laser and computer references as well as a list of synonyms (C.N.C., Weld, Numerical Control, etc.). In addition to the nine indexes searched in this way by computer, two major listings of abstracts were reviewed.

The laser literature was found to be divisable into several major categories. The first deals with the interaction of the laser beam with various materials. These studies are, in general, conducted with precision and provide a theoretical basis for laser welding, heat treating and surface treating processes. While none were directly applicable to this study, work on calculations of spot energy densities (Mostyaev & Uglov,1977) is critical to the selection of laser systems for welding with minimum distortion as discussed in Chapter II.

The next type of paper is concerned with the theory of the gas lasers. By far the best of these is "The High Power Carbon Dioxide Laser" by Patel (1968). His explanation of the quantum mechanical basis of laser operation is both lucid and rigorous.

There are many articles on applications of laser welding. Most of these, especially general process overviews tend to be little more than thinly disguised sales material for equipment manufacturers. The most useful and scholarly literature on computer controlled laser welding deals with the high speed spot welding of relay terminals using YAG or Ruby laser (Aeschliman & Monnier, 1976).

The computer literature gives references to welding mostly in terms of controlling gas metal arc and resistance welding. These proceses are usually closed loop controlled by monitoring and correcting output parameters. Most of the references to laser applications are as either sensing or output devices for computers. However, one excellent paper (Herbst, 1979) describes the computer control of a laser cutting operation.

Much of what purports to be production and manufacturing application of computers deals not with process control but with material control and cost accounting. Of those articles which actually deal with manufacturing process control, Koren (1979) provides one of the best explanations of the requirements for numerical control. Three of the best references on this topic are master's theses prepared at the University of New Haven (Hussain, 1977; Dezzant, 1973; O'Brien 1975).

The entire search yielded only one article on computer controlled laser welding of irregular shaped joints, (Krishnaswamy & Boccelli, 1977), other than the preliminary report on this project (Miller, 1979). It describes work on closing electrical component containers using a pulsed $CO_2$ laser with computer control. The purpose here, as in the recuperator program, was to produce hermetic seals. The material was Kovar, an iron base alloy with 29 percent nickel, 17 percent cobalt and 0.3 percent mangananese, and welds approximately 0.9 millimeters deep were required and successfully made.

## List of References

Aeschlimann, J. 1976. Automated welding of minute parts. Laser Focus. 12:3:33-36.

Dezzani, M. "Industrial Engineering Guide to the Min-Computer." Master's Thesis, University of New Haven, CT 1973.

Herbst, D. 1980. Computer control helps get the best out of laser profiler, Welder and Metal Fabrication. 48:4:223-36

Hussain, T. "An Investigation of the General Design Criteria for a Micro-computer Based Process." Master;s Thesis, University of New Haven, CT., 1977.

Koren, Y. 1979. Design of computer control for manufacturing systems. Transactions of the A.S.M.E. 101:326-32.

Krishnaswamy, H. and Boccelli, V. 1977. Micro-Circuit flat pack sealing by laser welding. S.A.M.P.E. Quarterly. July, 11-19.

Miller, J. 1979. Laser welding cuts costs 63 percent U.S. Army Mantech Journal. 4:1:12-20.

Mostyaev, V. and Uglov. A. 1977. Evaluation of therman processes 6aking place in pulsed laser seam welding. Weld Production. 24:10:1-3.

O'Brien, W. "Thje Micro Computer as Applied to Automated Control Systems. "Master's Thesis, University of New Haven, CT 1975.

Patel, C. 1968. High power carbon dioxide lasers. Scientific American. 219:22-33.

DISTRIBUTION LIST

| | Copies |
|---|---|
| DEFENSE DOCUMENTATION CENTER<br>ATTN: TIPDR<br>Cameron Station<br>Alexandria, VA 22314 | 12 |
| Commander<br>US ARMY MATERIEL DEVELOPMENT AND READINESS COMMAND<br>ATTN: DRCMT-M<br>5001 Eisenhower Avenue<br>Alexandria, VA 22333 | 1 |
| Director<br>US ARMY MATERIALS AND MECHANICS RESEARCH CENTER<br>ATTN: DRXMR-M<br>Watertown, MA 02172 | 2 |
| Director<br>US ARMY INDUSTRIAL BASE ENGINEERING ACTIVITY<br>ATTN: DRXIB-MT<br>Rock Island Arsenal<br>Rock Island, IL 61299 | 3 |
| Commander<br>US ARMY INDUSTRIAL RESOURCES OFFICES<br>ATTN: Code 044<br>Philadelphia, PA 19112 | 1 |
| Commander<br>AIR FORCES MATERIALS LABORATORY<br>ATTN: LTM<br>Wright-Patterson AFB, OH 45433 | 1 |
| Commander<br>US ARMY TACOM<br>ATTN: DRSTA-UL (Technical Library)<br>Warren, MI 48090 | 2 |
| Commander<br>ROCK ISLAND ARSENAL<br>ATTN: SARRI-ENM-T, R. Kalkan, Jr.<br>Rock Island, IL | 1 |

Commander<br>USA Aviation Research & Development<br>  Command<br>Mr. John Conroy, DRDAV-QF<br>4300 Goodfellow Blvd.<br>St. Louis, MO 63120 — 2

Commander<br>Harry Diamond Laboratories<br>ATTN: Library<br>Washington, DC 20438 — 1